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Gorrell et al.

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(54) **SWITCHING MICRO-RESONANT STRUCTURES BY MODULATING A BEAM OF CHARGED PARTICLES**

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(73) Assignee: **Advanced Plasmonics, Inc.**, Gainesville, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **13/774,593**

(22) Filed: **Feb. 22, 2013**

(65) **Prior Publication Data**

US 2013/0161529 A1 Jun. 27, 2013

Related U.S. Application Data

(63) Continuation of application No. 12/329,866, filed on Dec. 8, 2008, now Pat. No. 8,384,042, which is a continuation of application No. 11/325,534, filed on Jan. 5, 2006, now Pat. No. 7,586,097.

(51) **Int. Cl.**

H01J 31/00	(2006.01)
H01J 27/02	(2006.01)
H01J 29/70	(2006.01)
H01J 25/00	(2006.01)

(52) **U.S. Cl.**
CPC ***H01J 27/022*** (2013.01); ***H01J 31/00*** (2013.01); ***H01J 29/70*** (2013.01); ***H01J 25/00*** (2013.01)

(58) **Field of Classification Search**
CPC H01J 27/00; H01J 27/02; H01J 27/022; H01J 27/16; H01J 29/00; H01J 29/70; H01J 29/701; H01J 29/72; H01J 29/80; H01J 31/00
USPC .... 250/396 R, 493.1, 495.1, 397; 315/500, 315/5.43, 505
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,241,244 A * 8/1993 Cirri 315/111.41

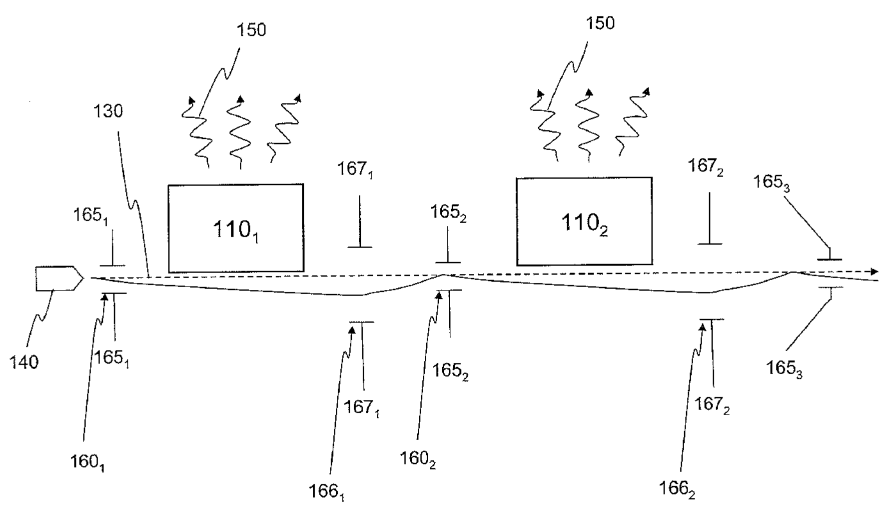
* cited by examiner

Primary Examiner — David H Vu
(74) *Attorney, Agent, or Firm* — Davidson Berquist; Jackson & Gowdey, LLP

(57) **ABSTRACT**

When using micro-resonant structures, a resonant structure may be turned on or off (e.g., when a display element is turned on or off in response to a changing image or when a communications switch is turned on or off to send data different data bits). Rather than turning the charged particle beam on and off, the beam may be moved to a position that does not excite the resonant structure, thereby turning off the resonant structure without having to turn off the charged particle beam. In one such embodiment, at least one deflector is placed between a source of charged particles and the resonant structure(s) to be excited. When the resonant structure is to be turned on (i.e., excited), the at least one deflector allows the beam to pass by undeflected. When the resonant structure is to be turned off, the at least one deflector deflects the beam away from the resonant structure by an amount sufficient to prevent the resonant structure from becoming excited.

15 Claims, 34 Drawing Sheets



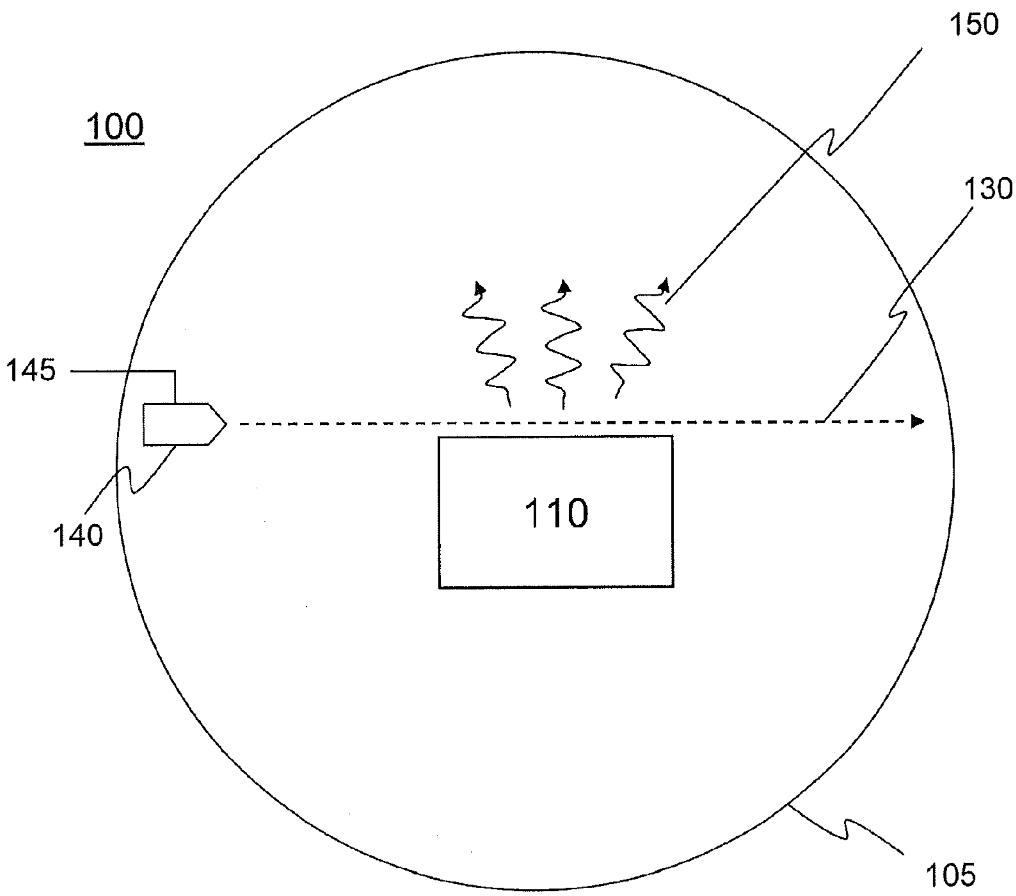


Figure 1

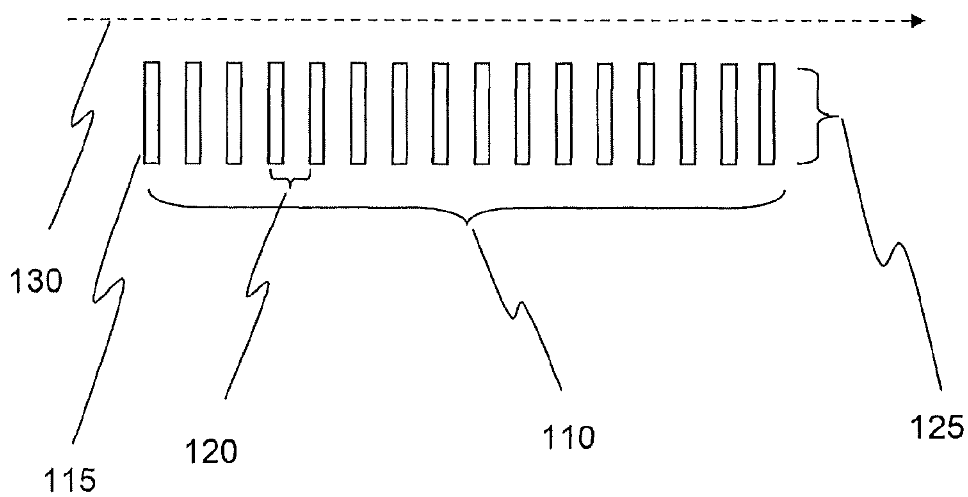


Figure 2A

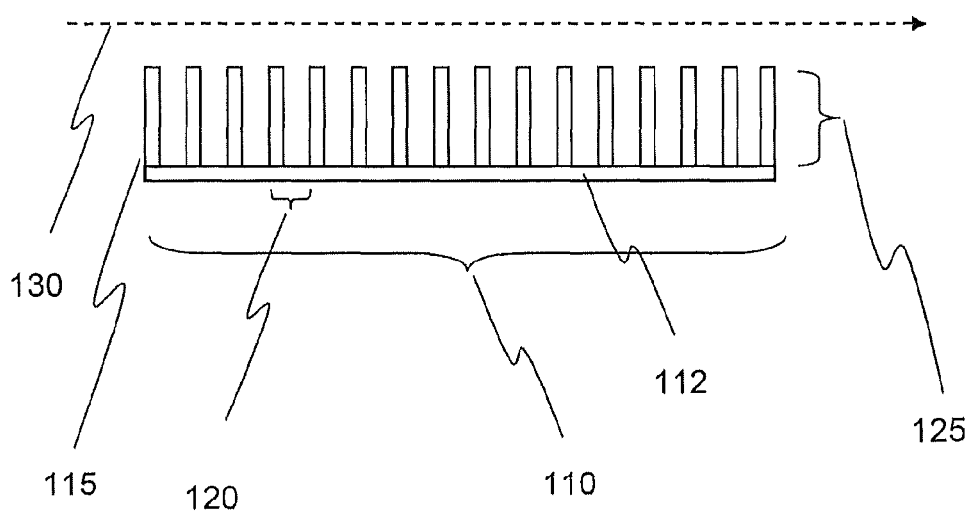


Figure 2B

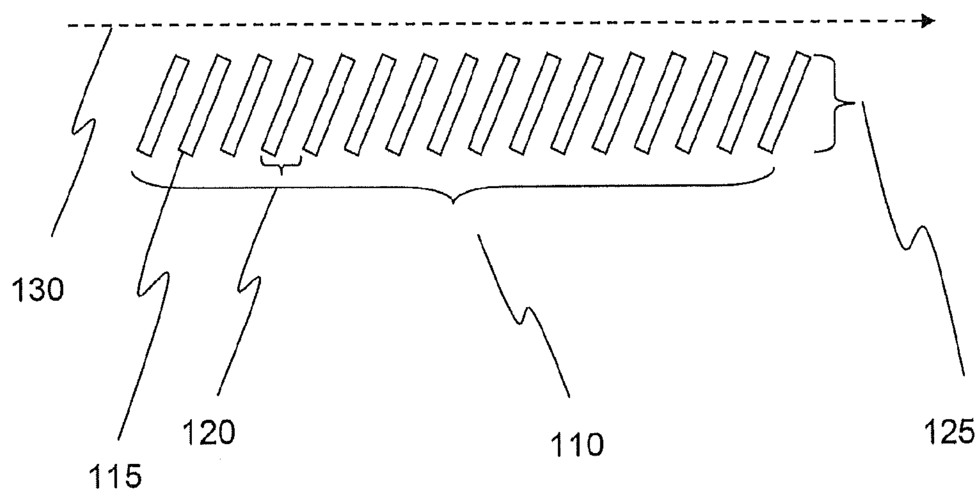


Figure 2C

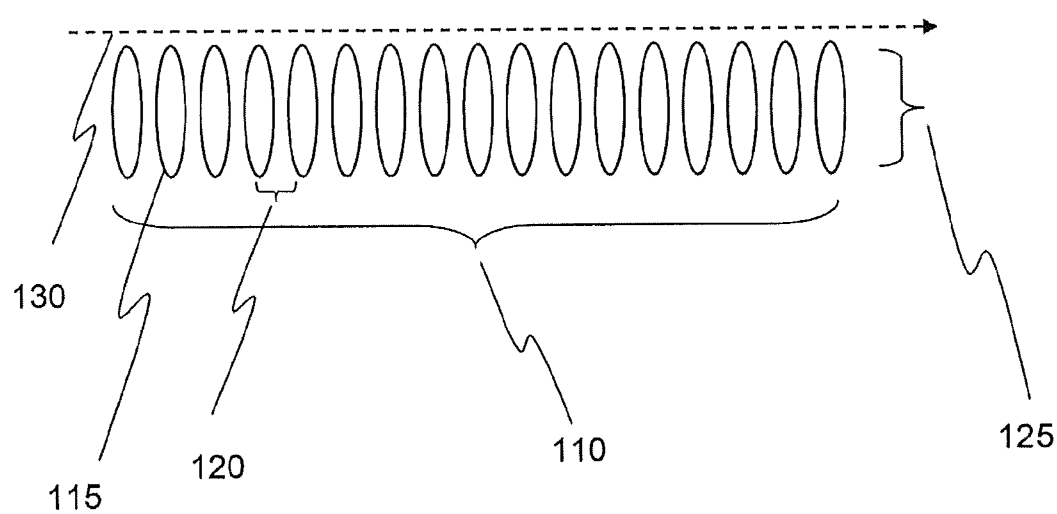


Figure 2D

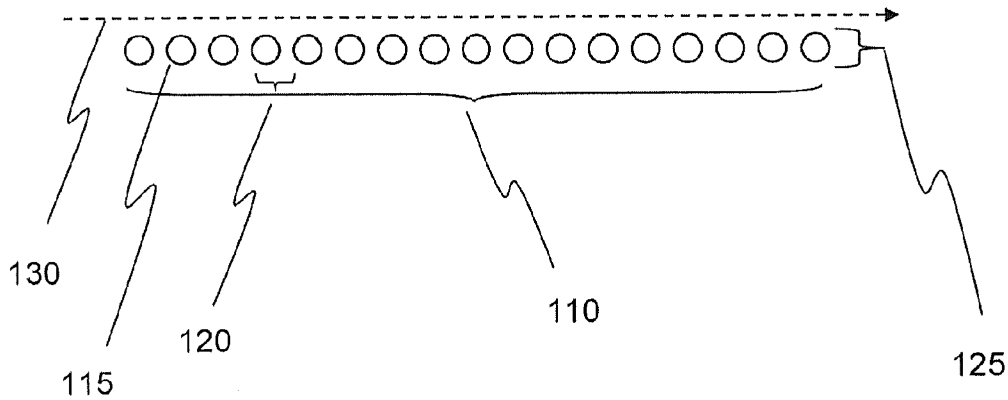
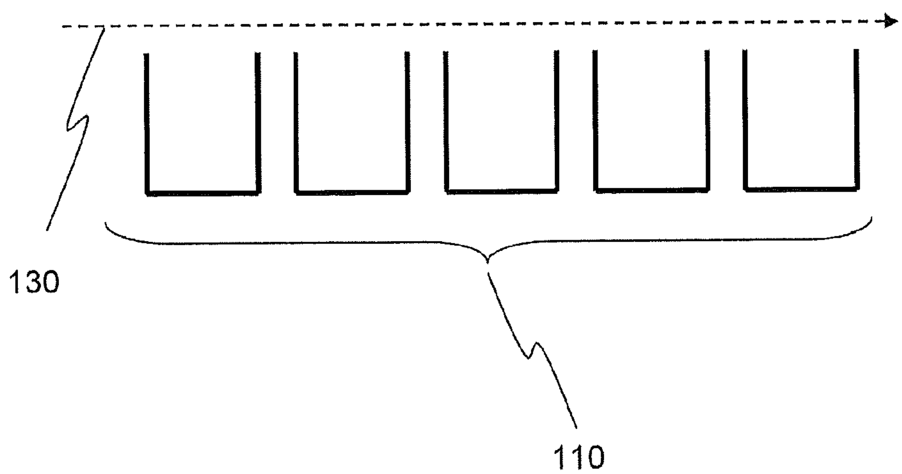


Figure 2E



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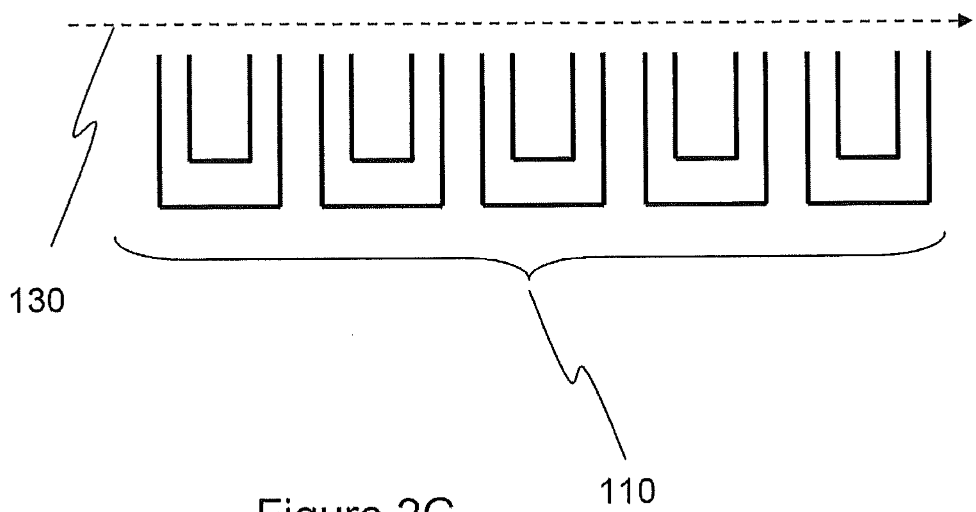

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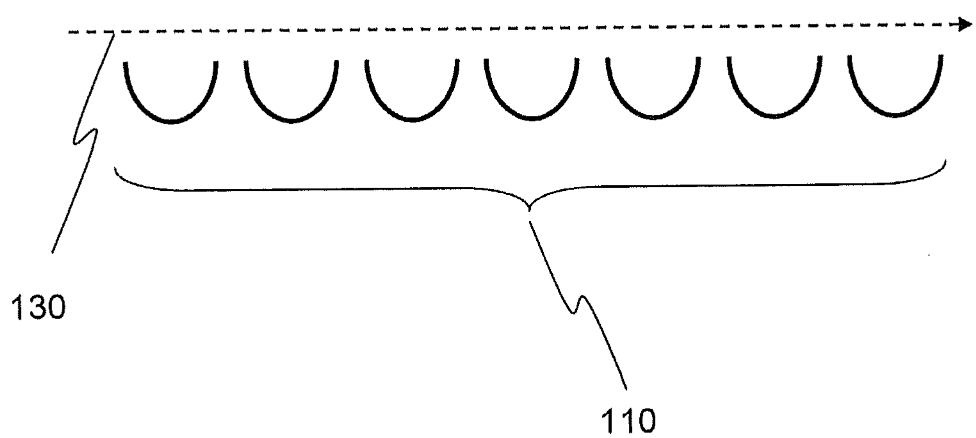

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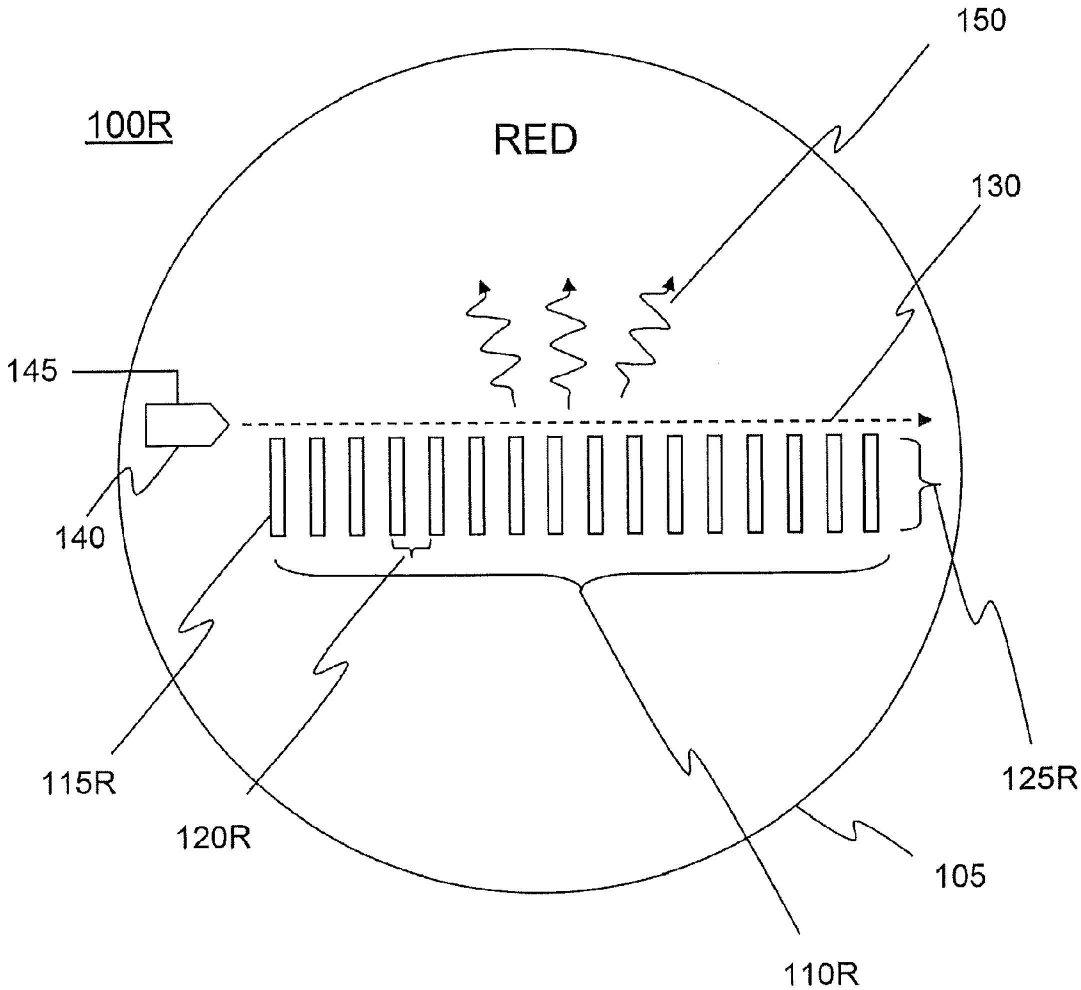

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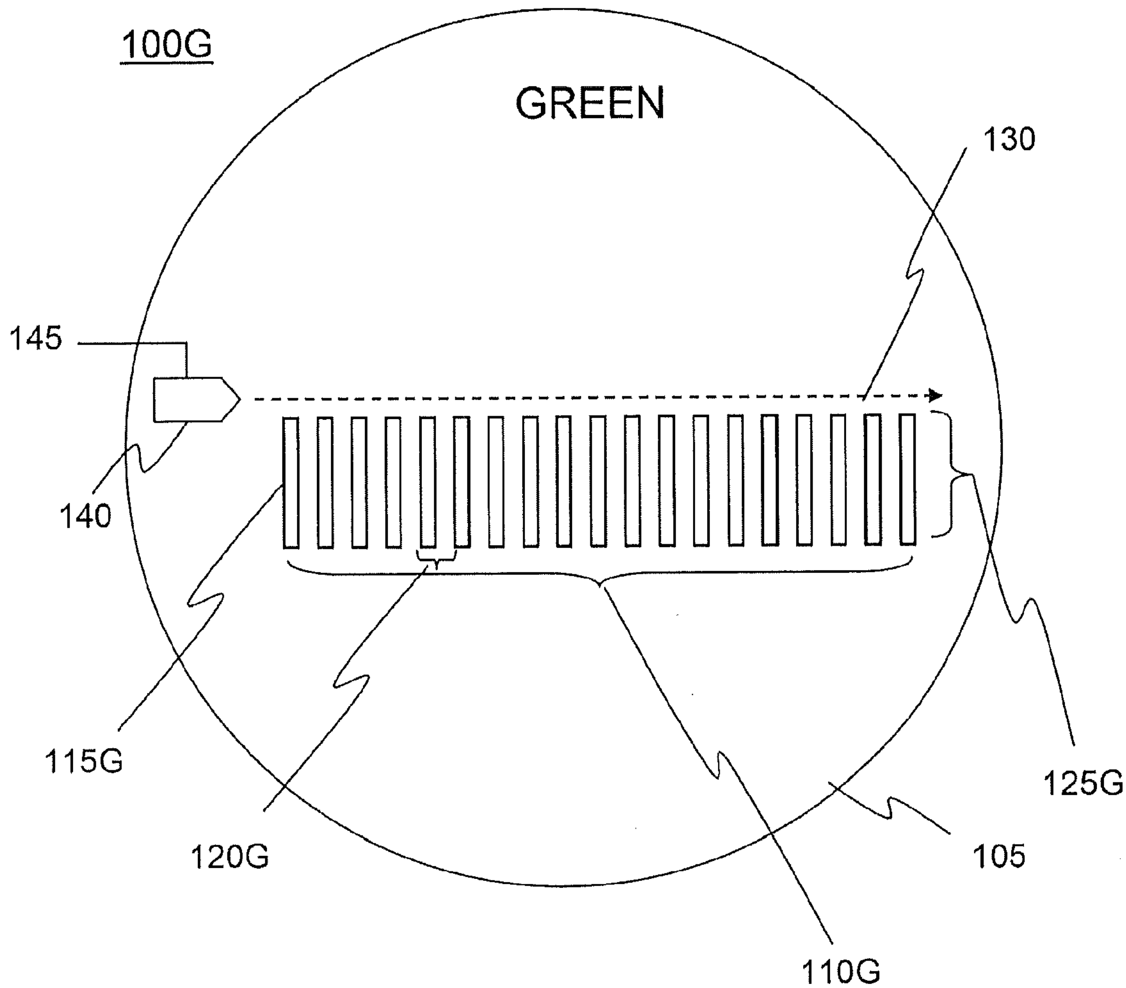

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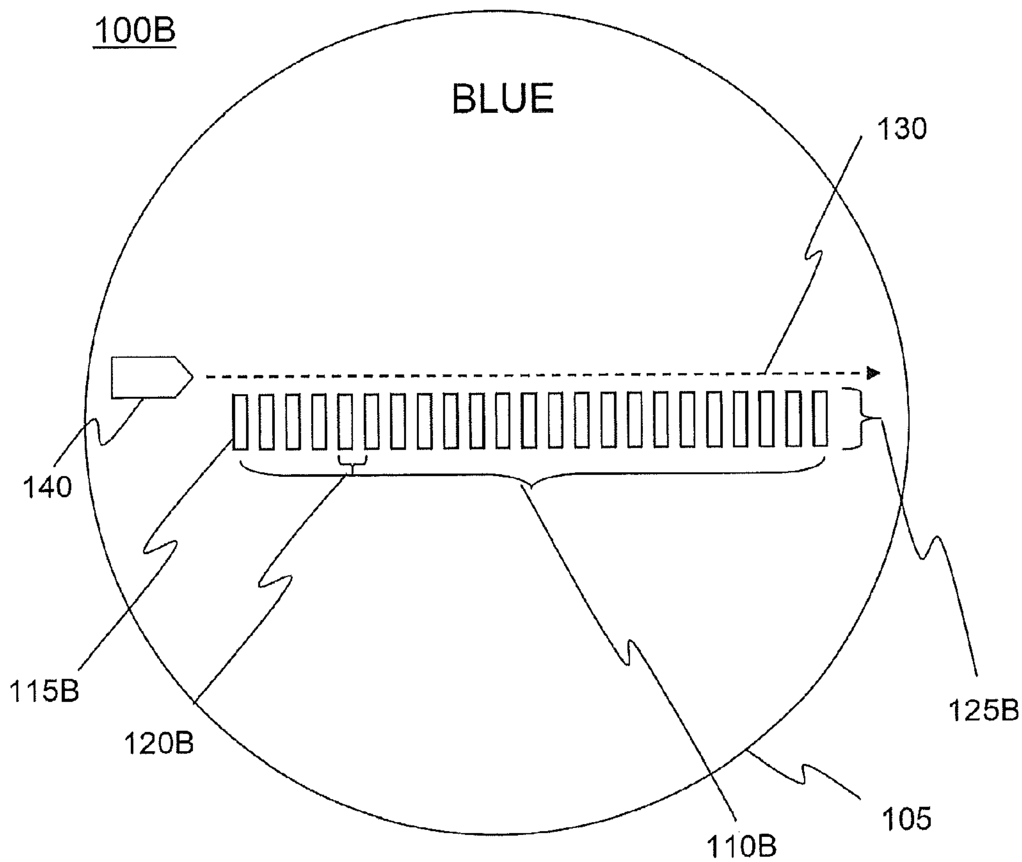

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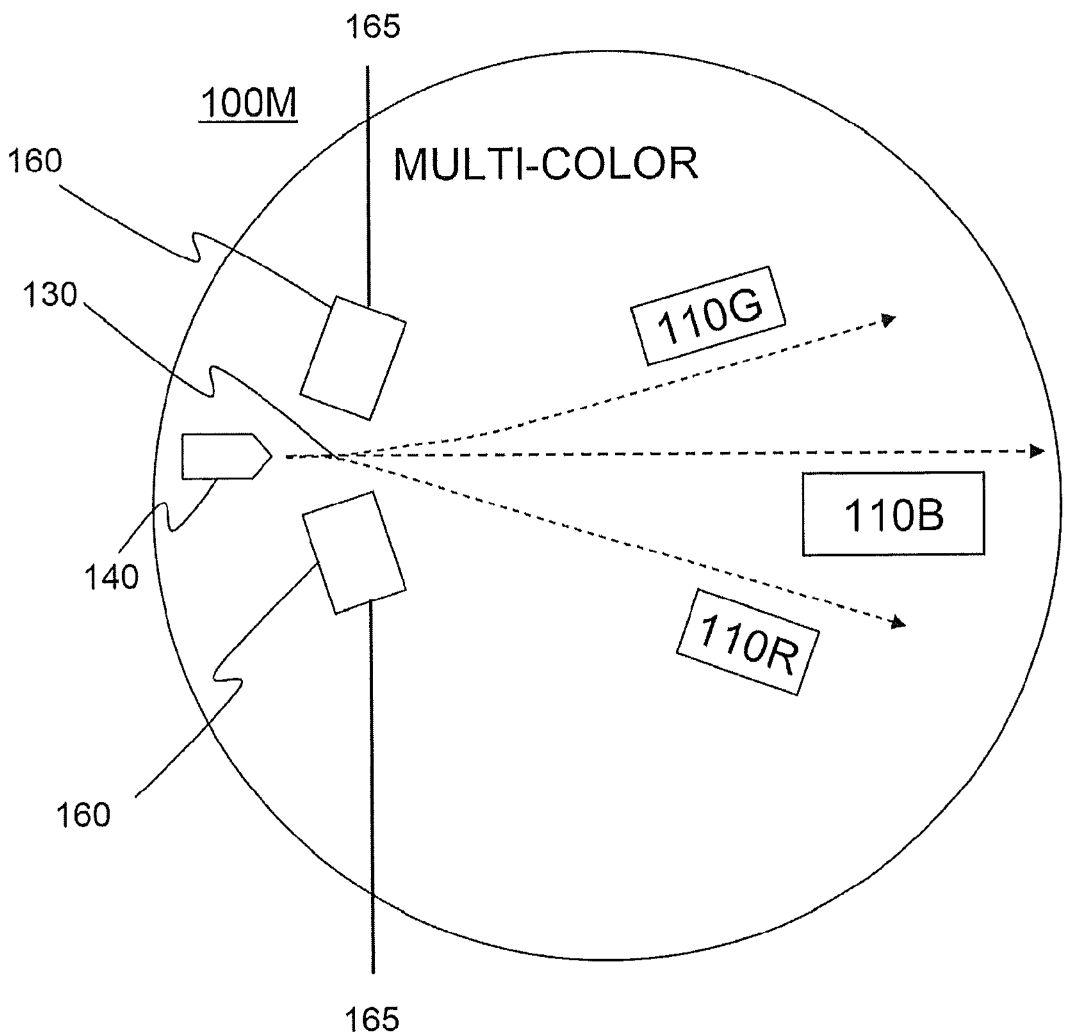

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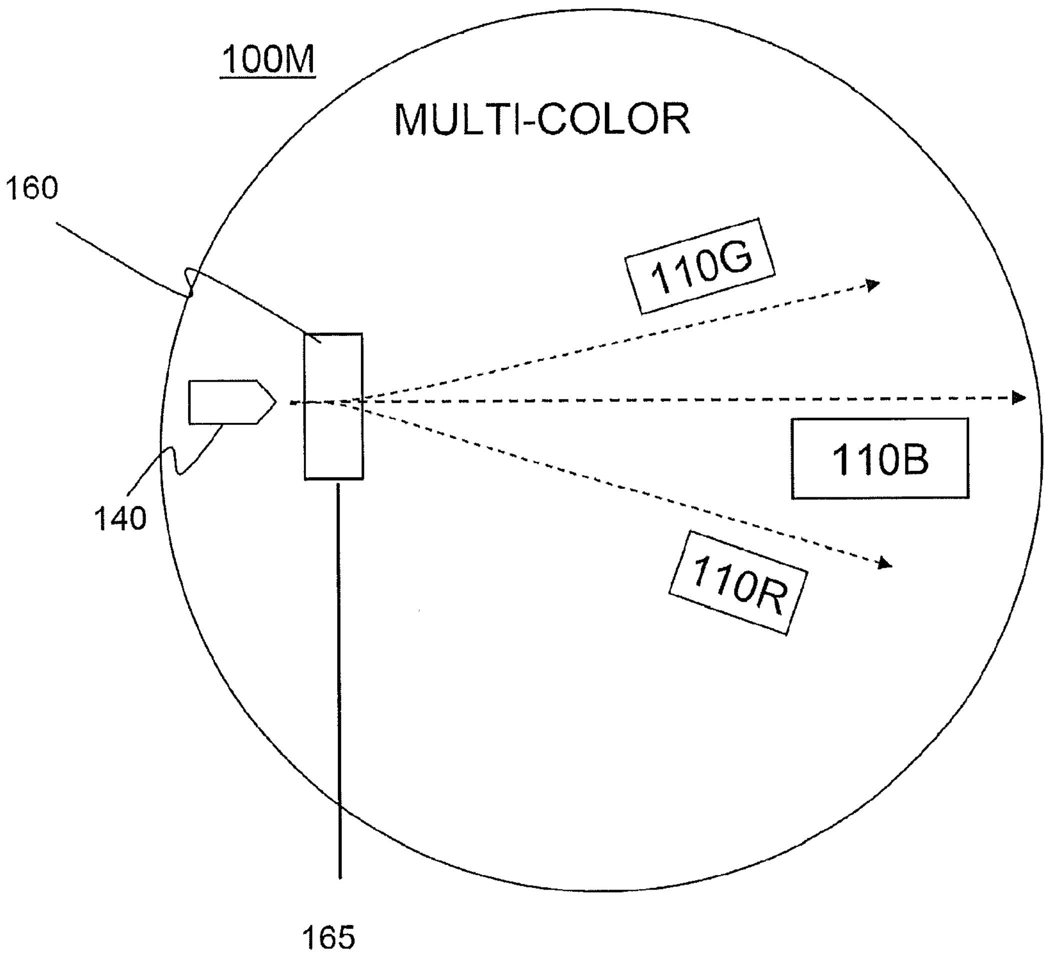

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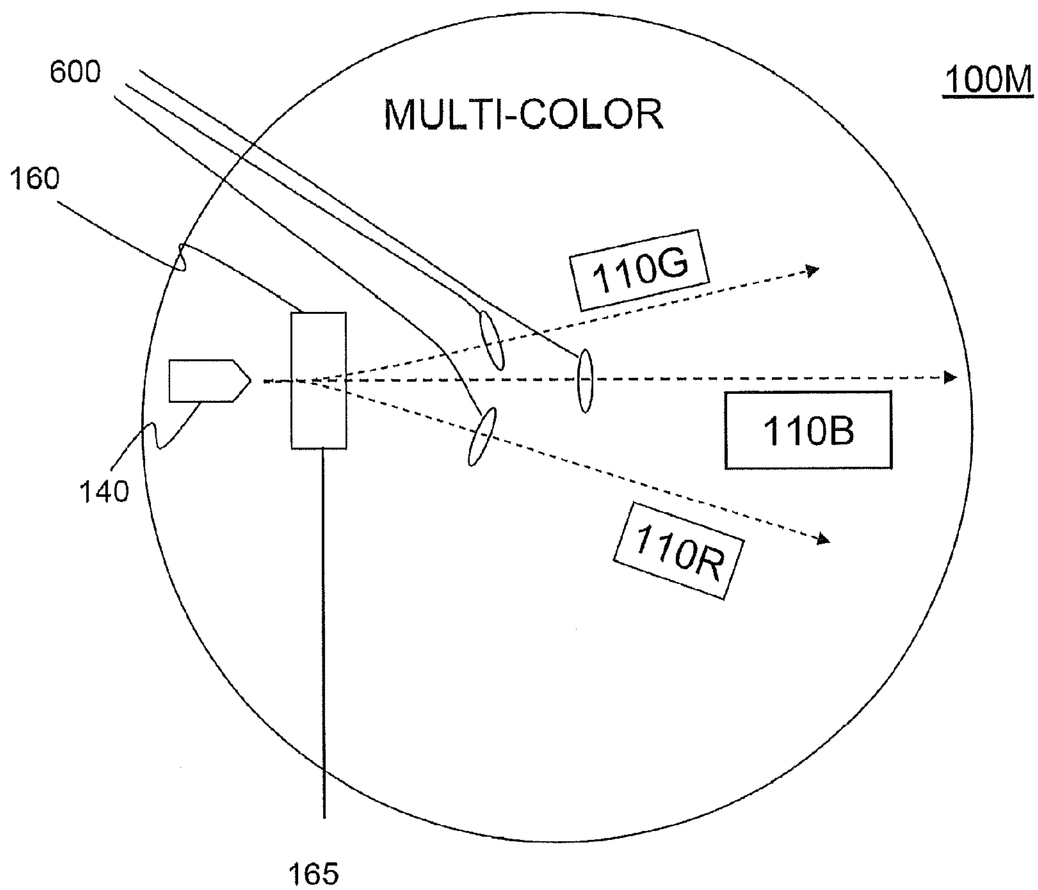

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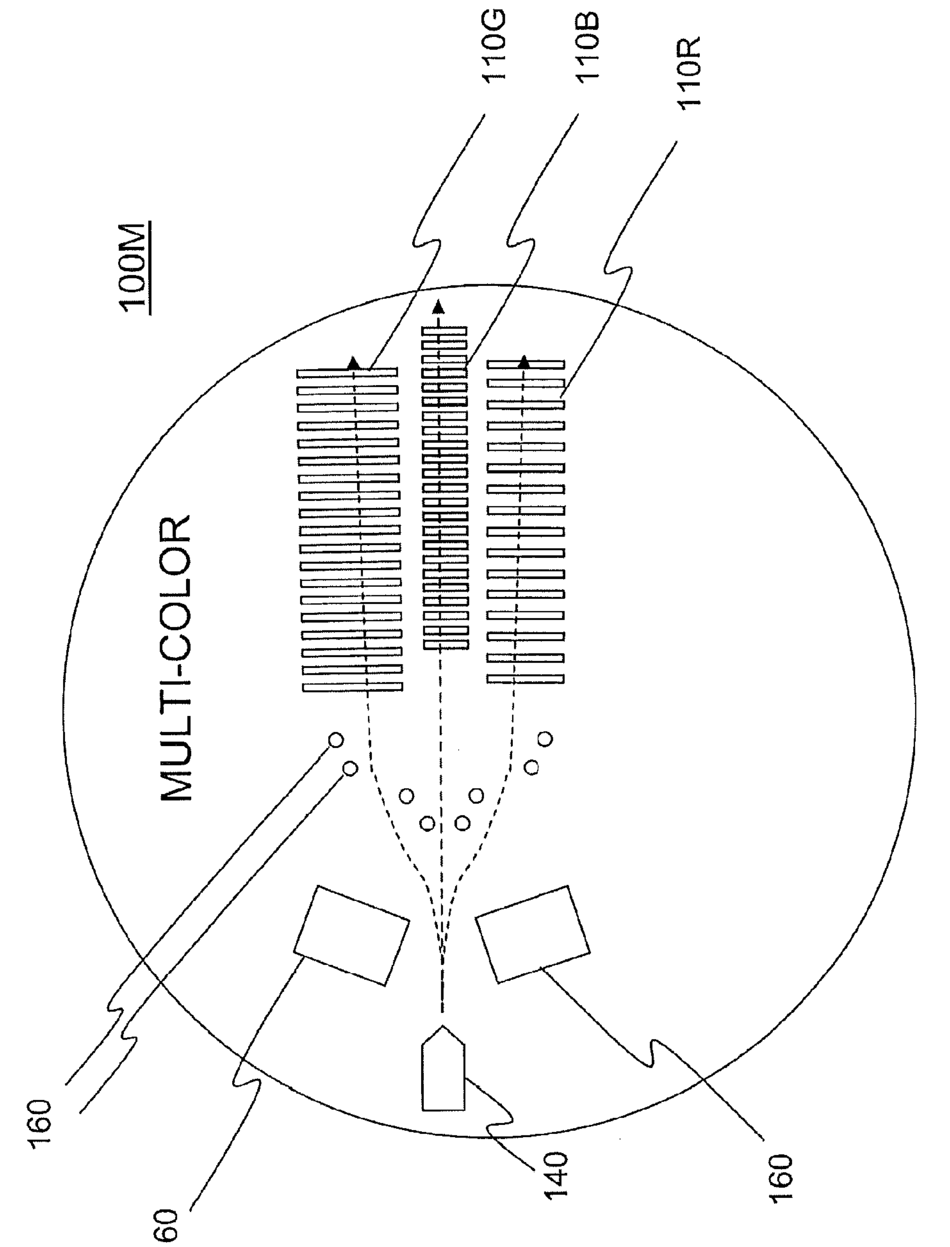

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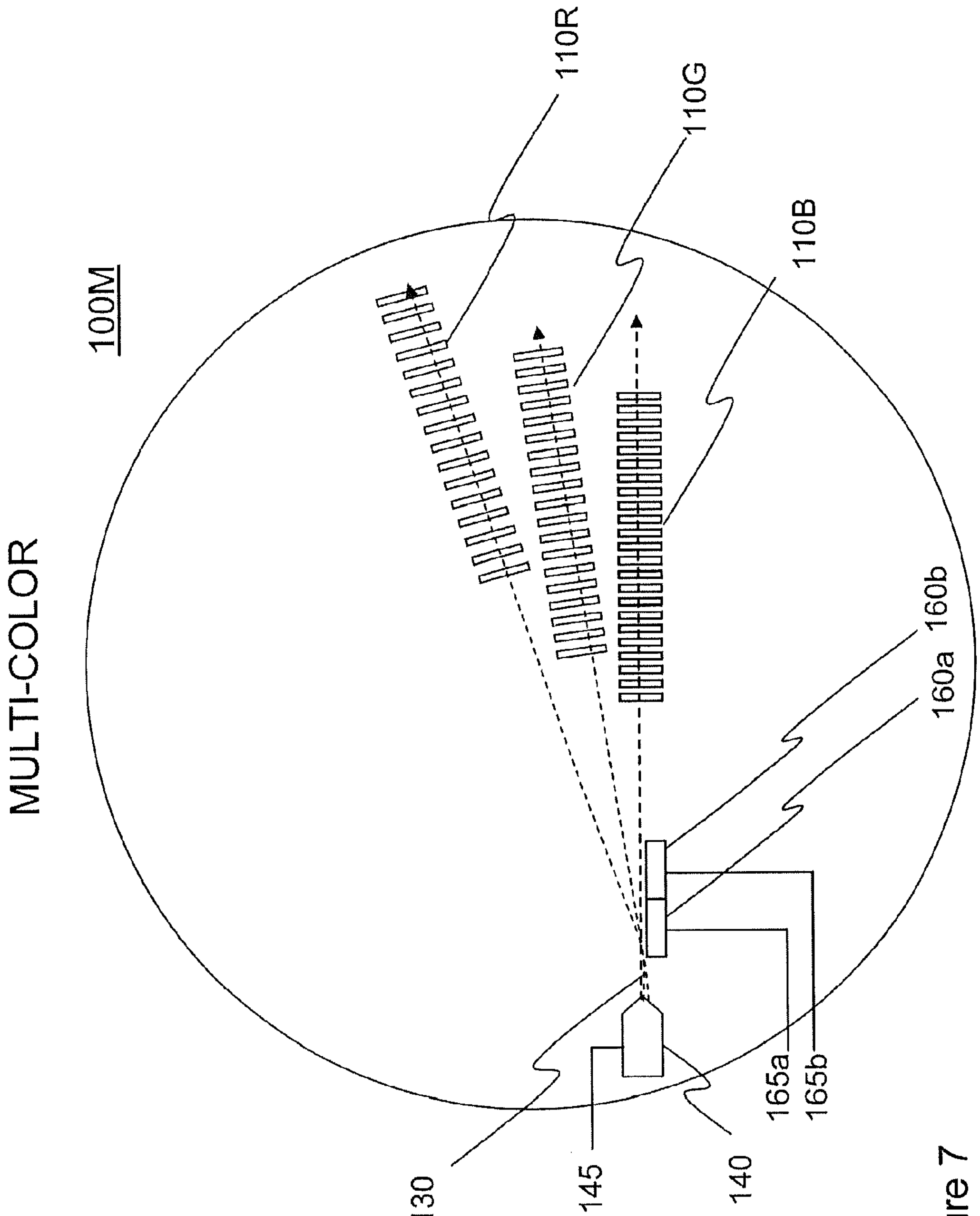
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110G
110B
160a
160b
165a
165b
130
145
140

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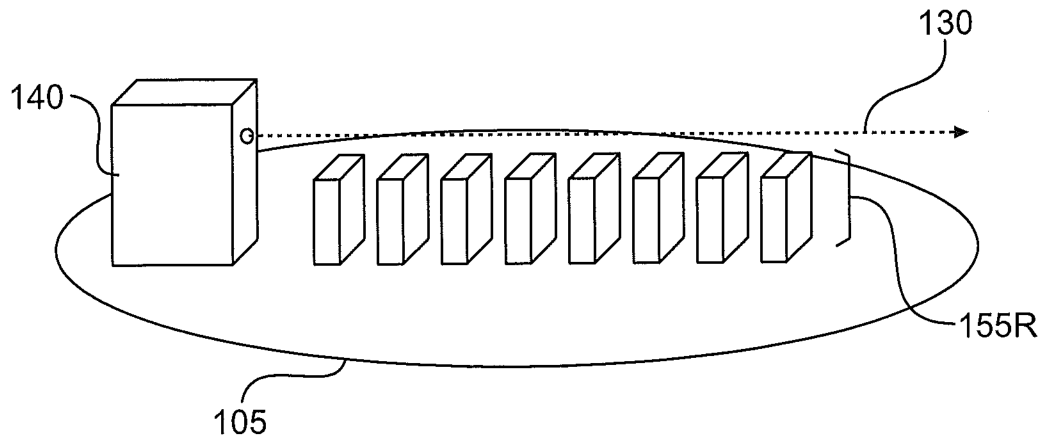

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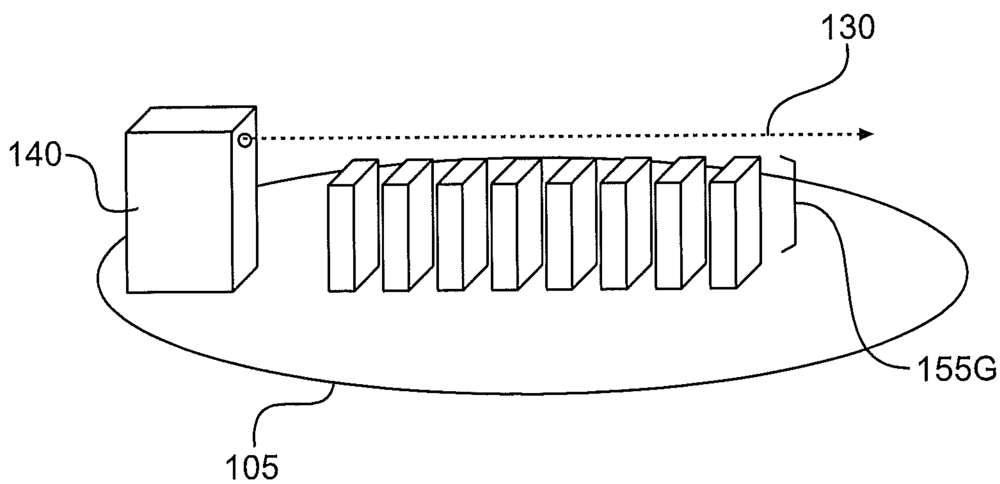

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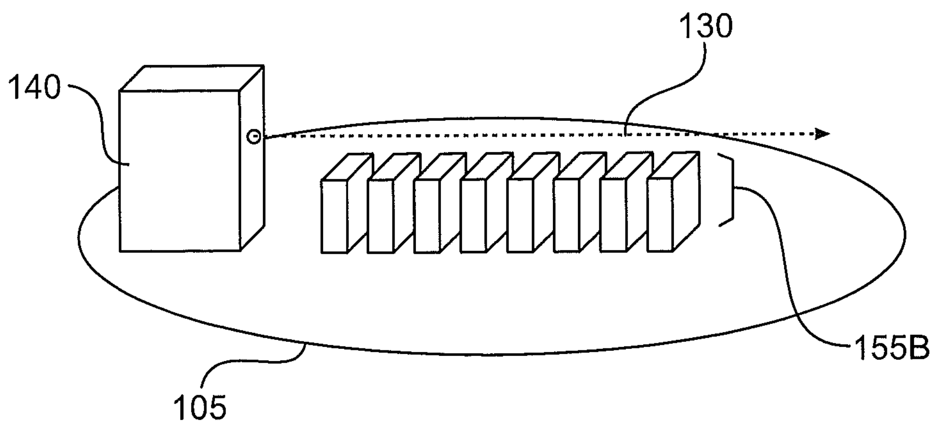

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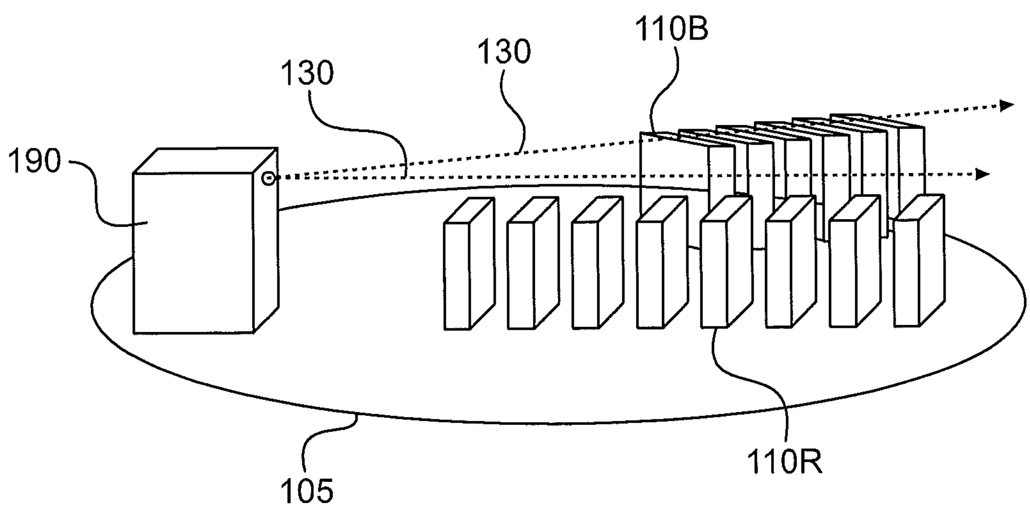

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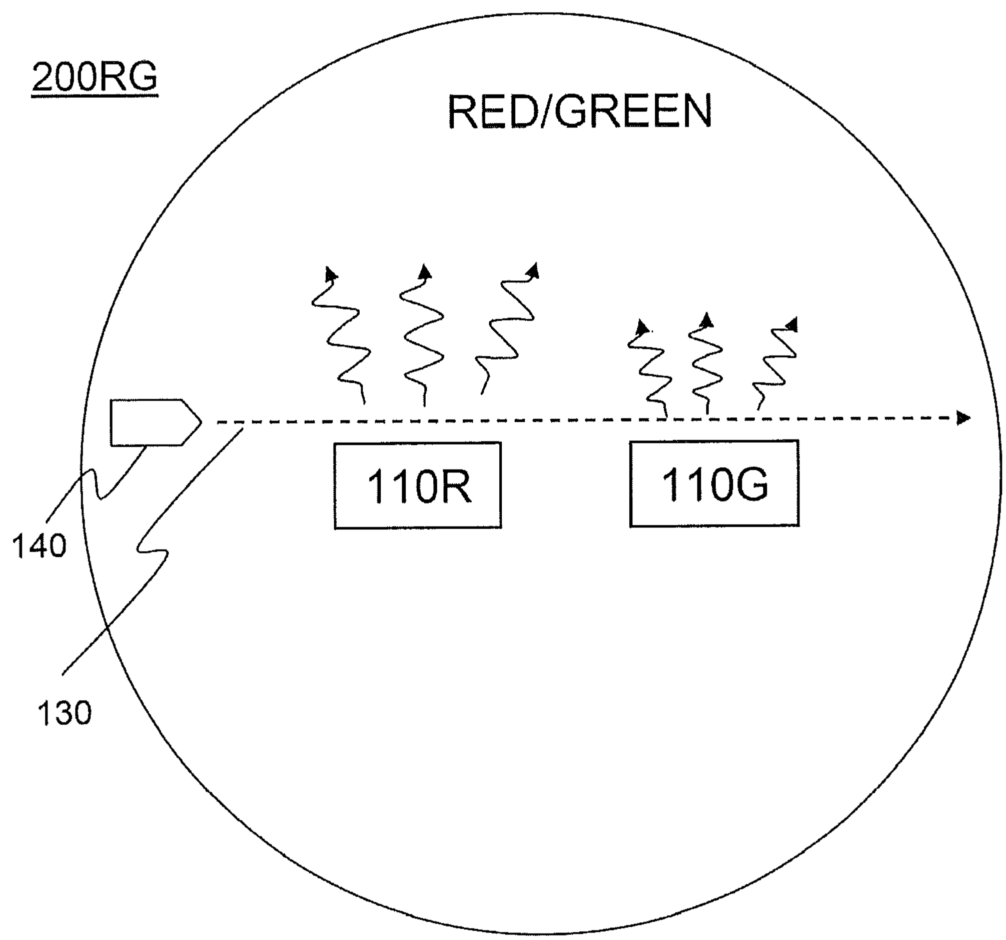

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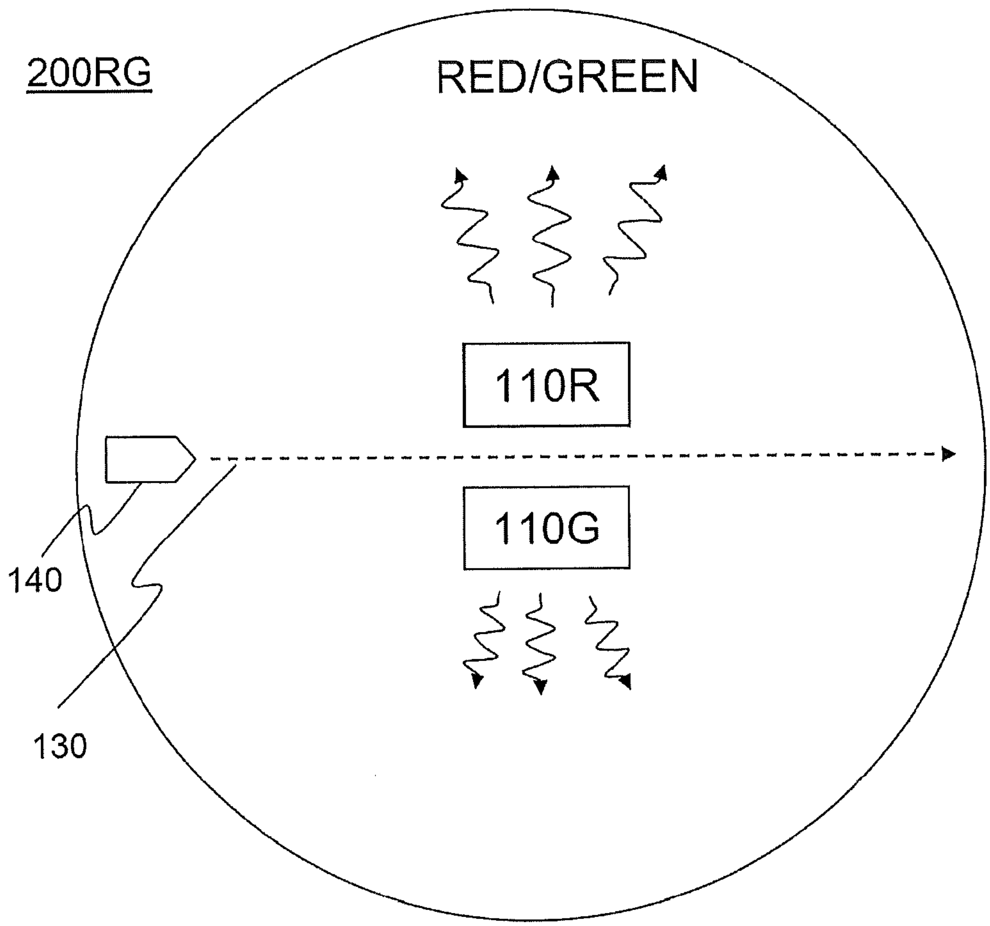

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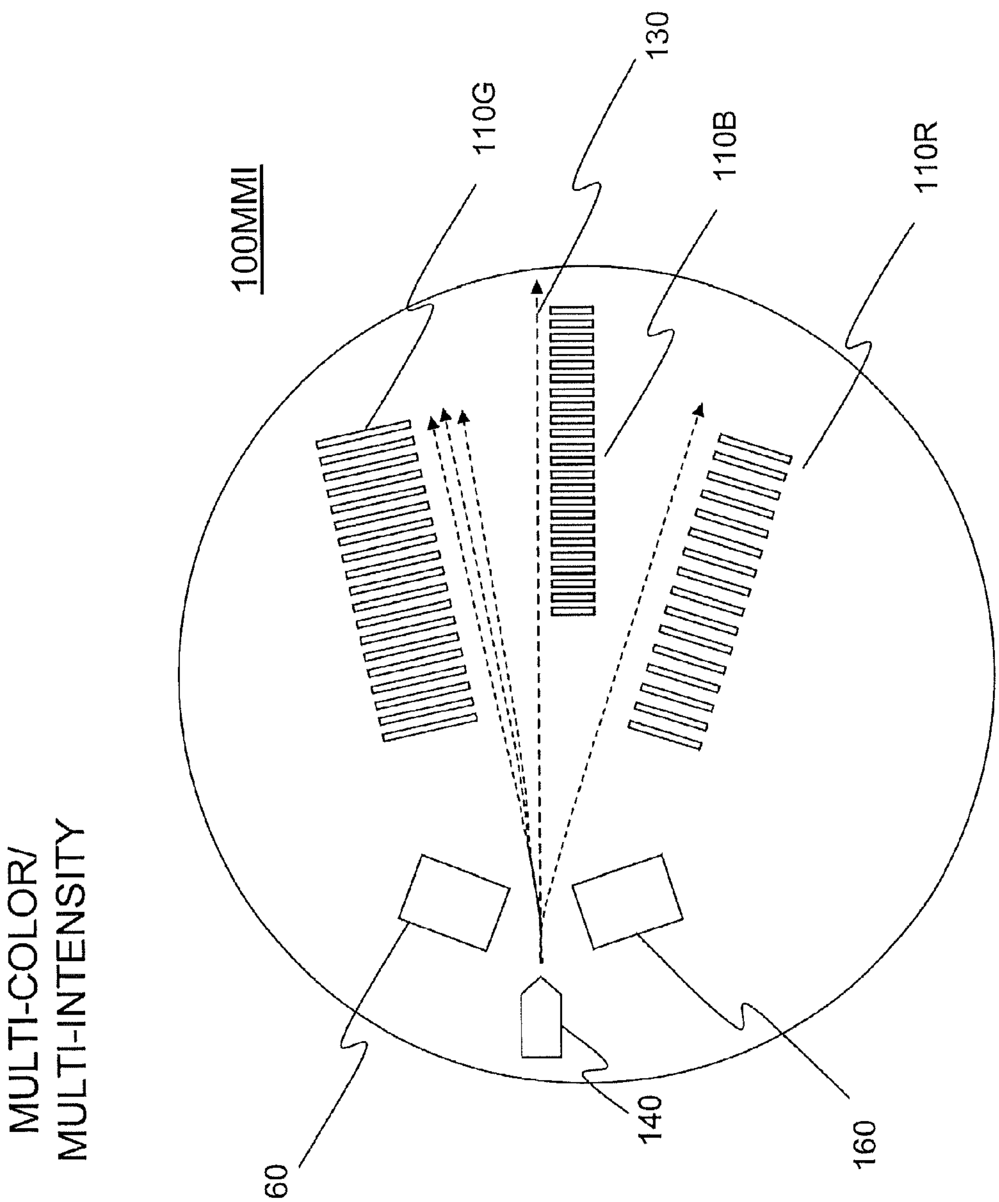
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MULTI-INTENSITY
100MMI
110G
130
110B
110R
160
140
160

Figure 14

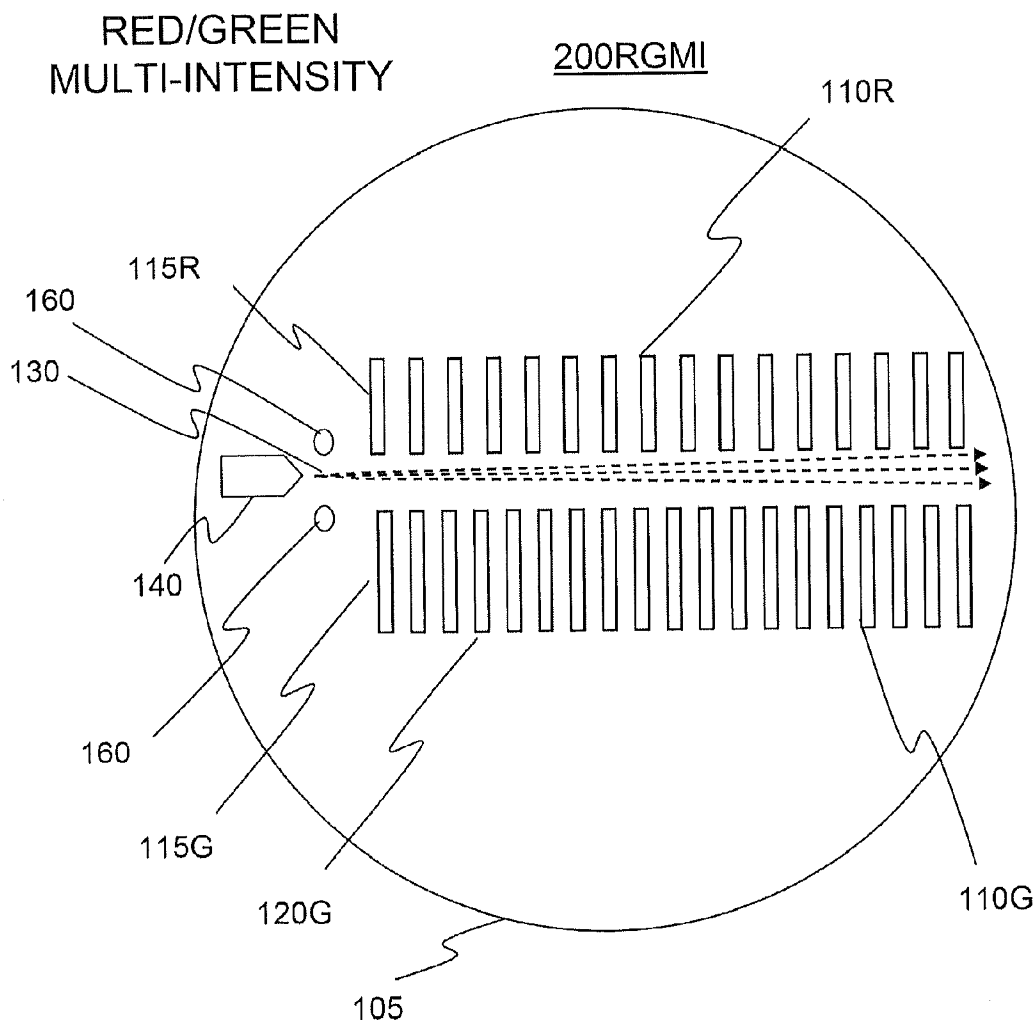
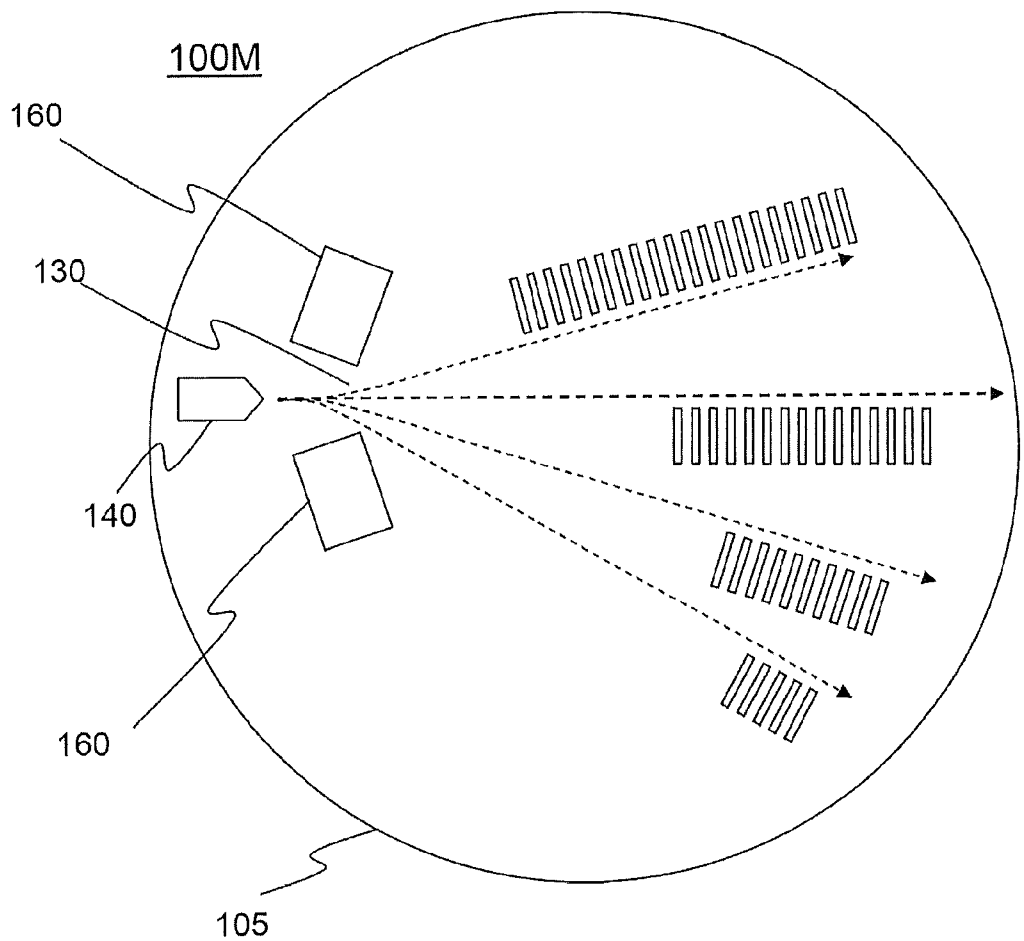

RED/GREEN
MULTI-INTENSITY
200RGMI
110R
115R
160
130
140
160
115G
120G
110G
105

Figure 15

MULTI-INTENSITY



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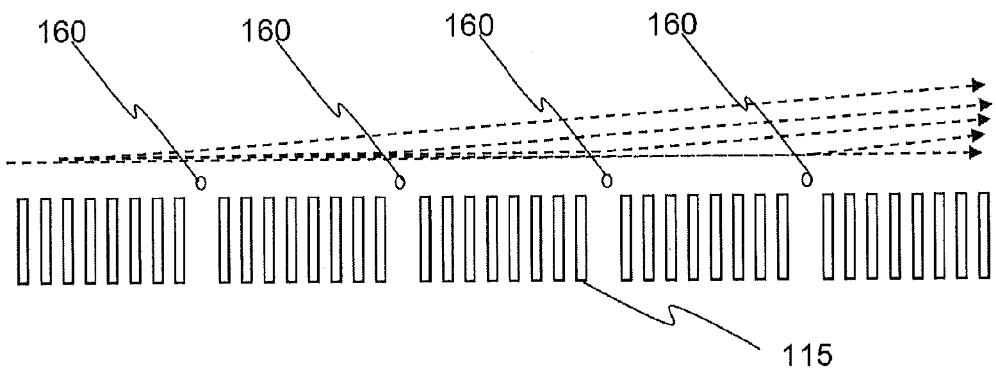

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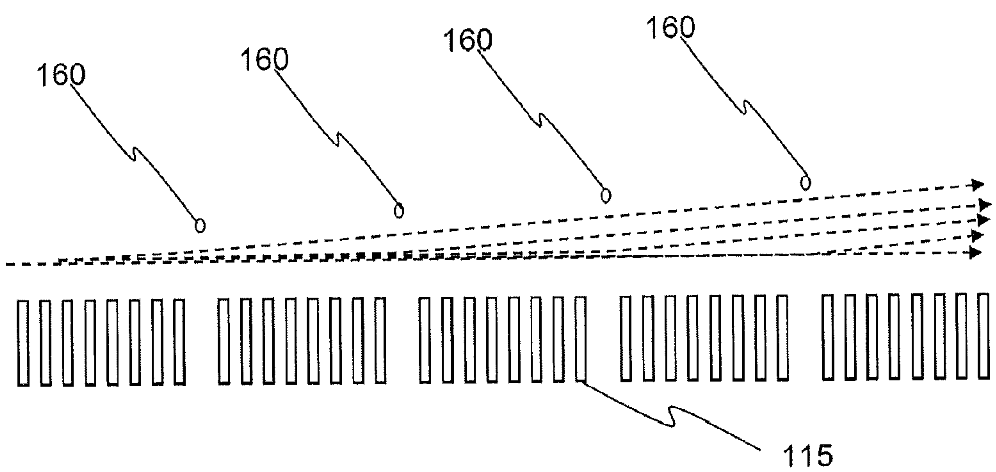


Figure 17B

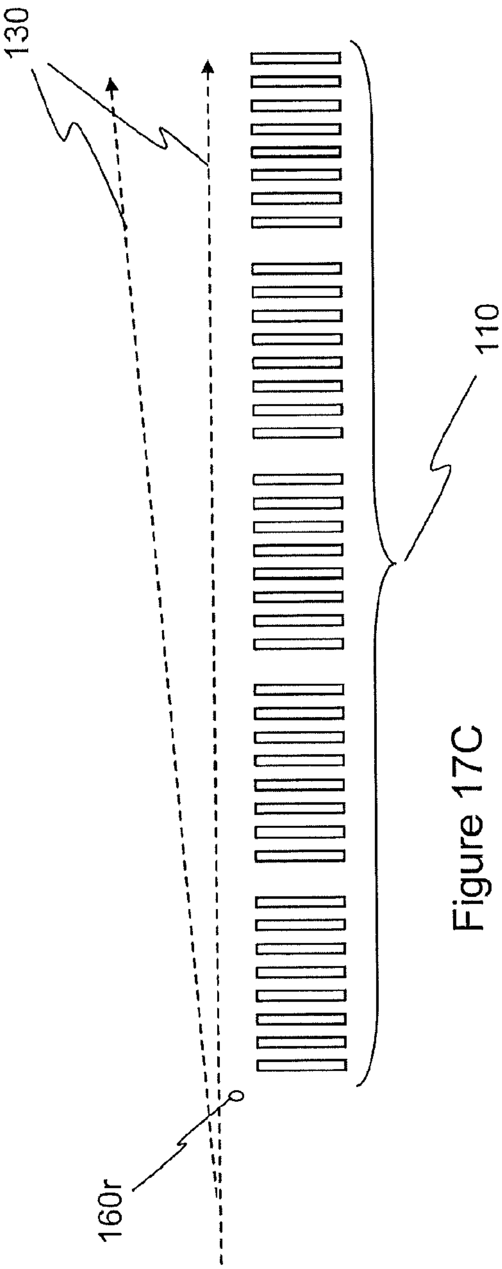


Figure 17C

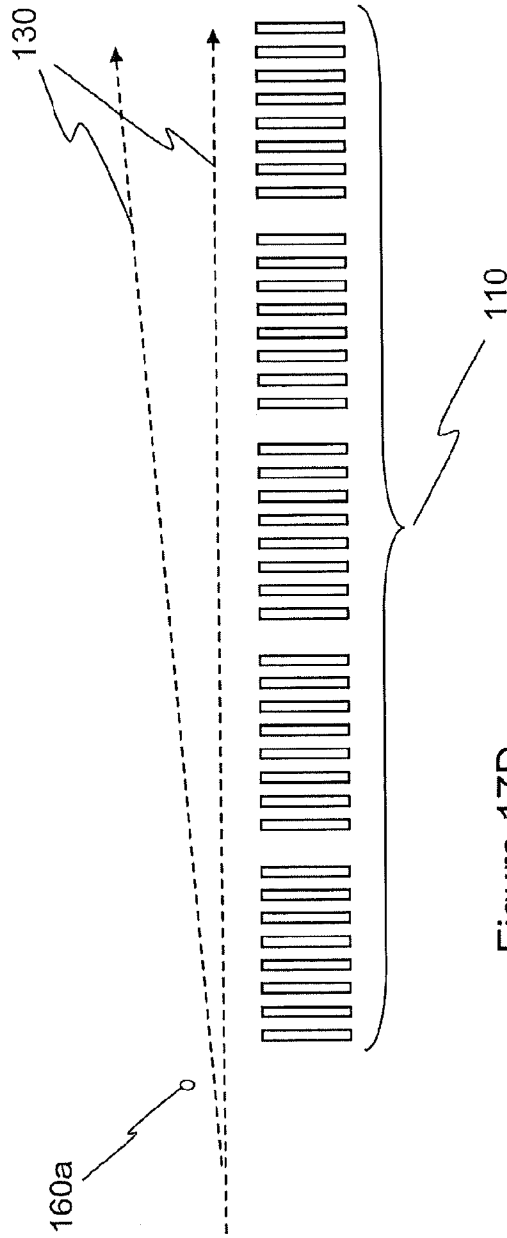
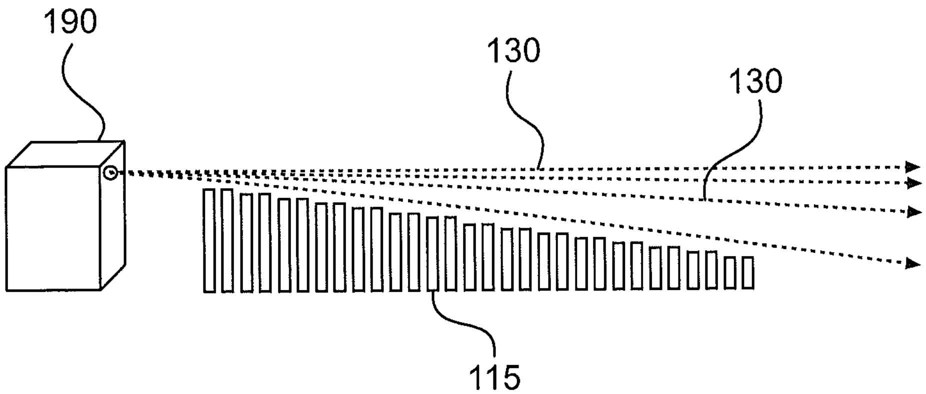


Figure 17D



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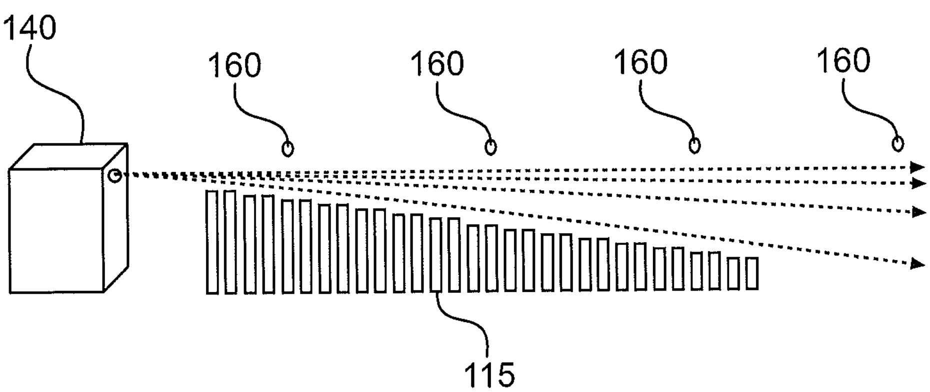

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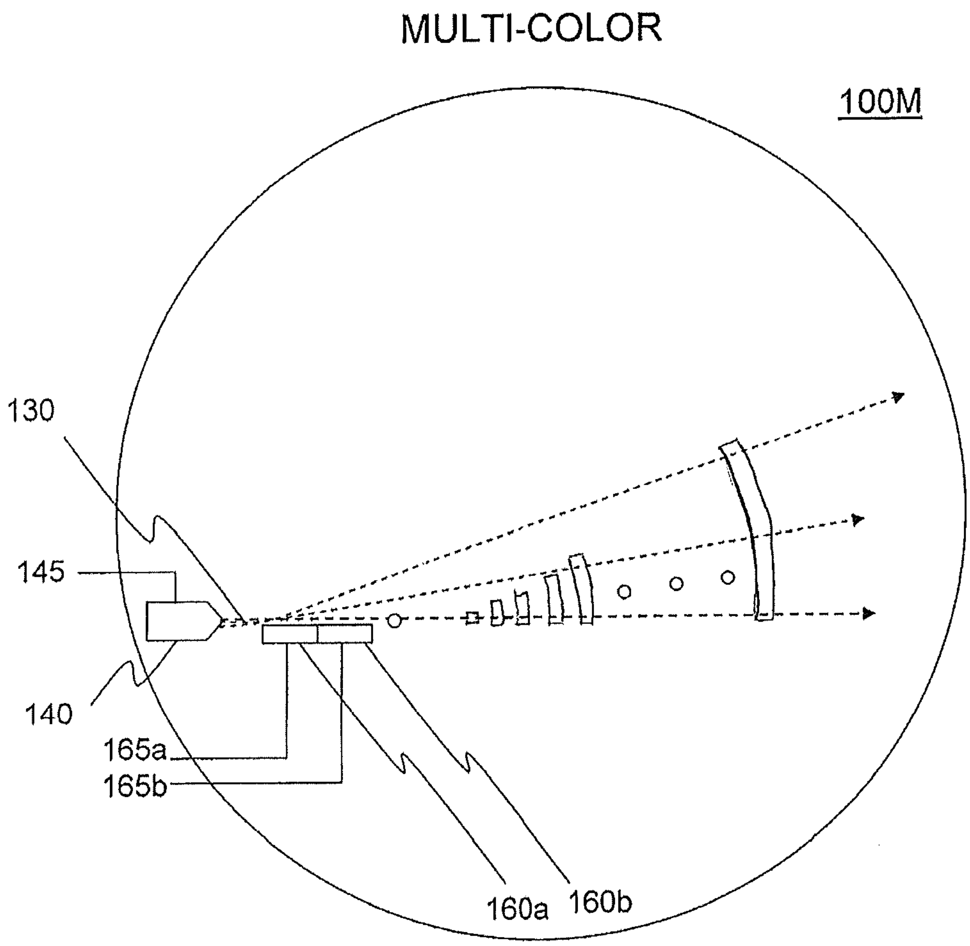
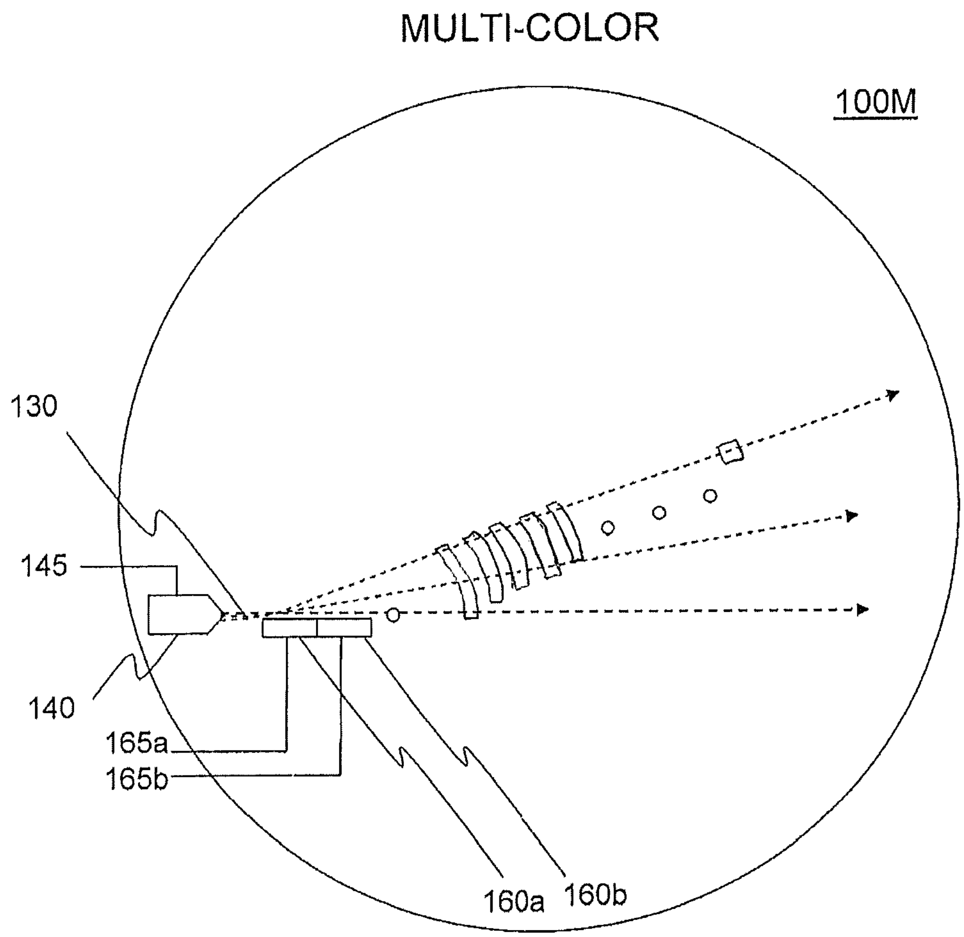


Figure 19A



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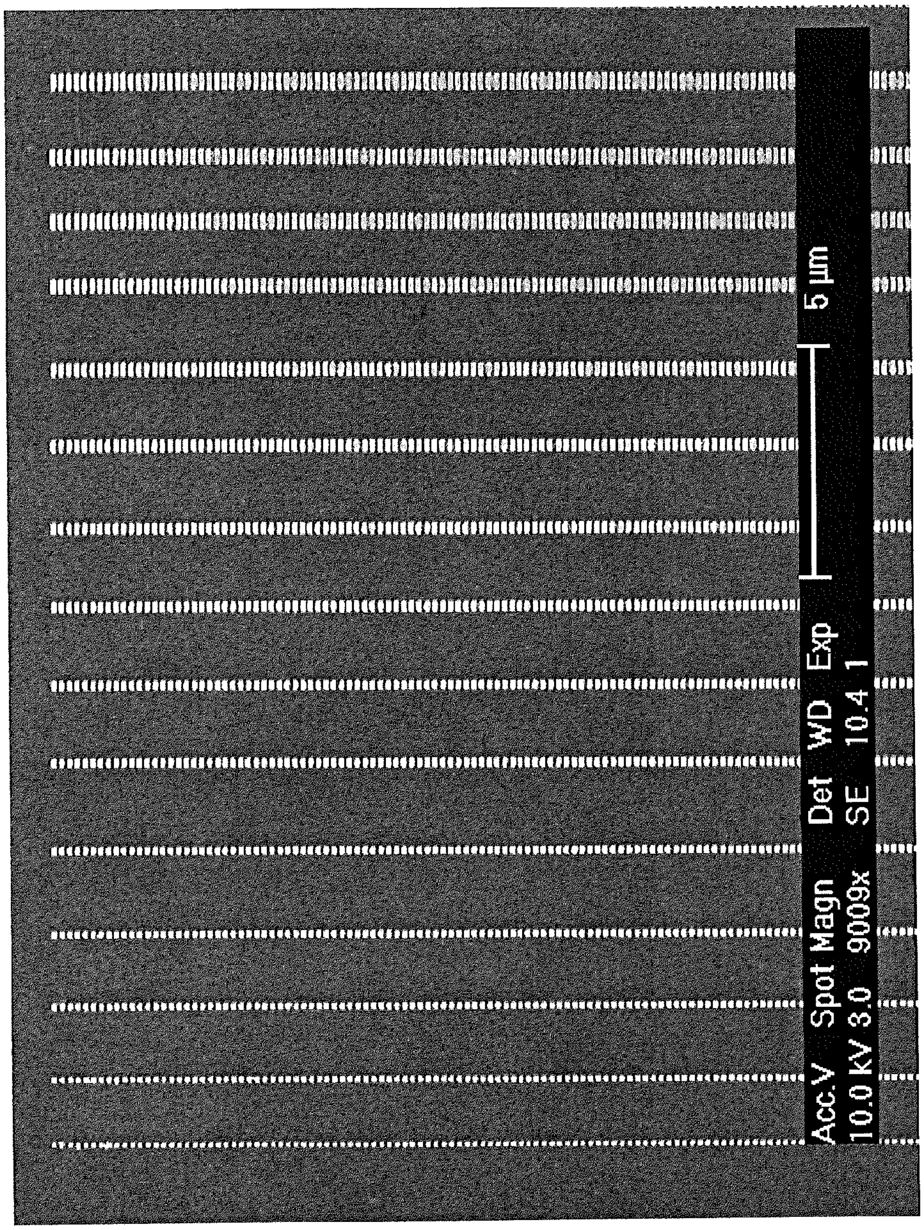

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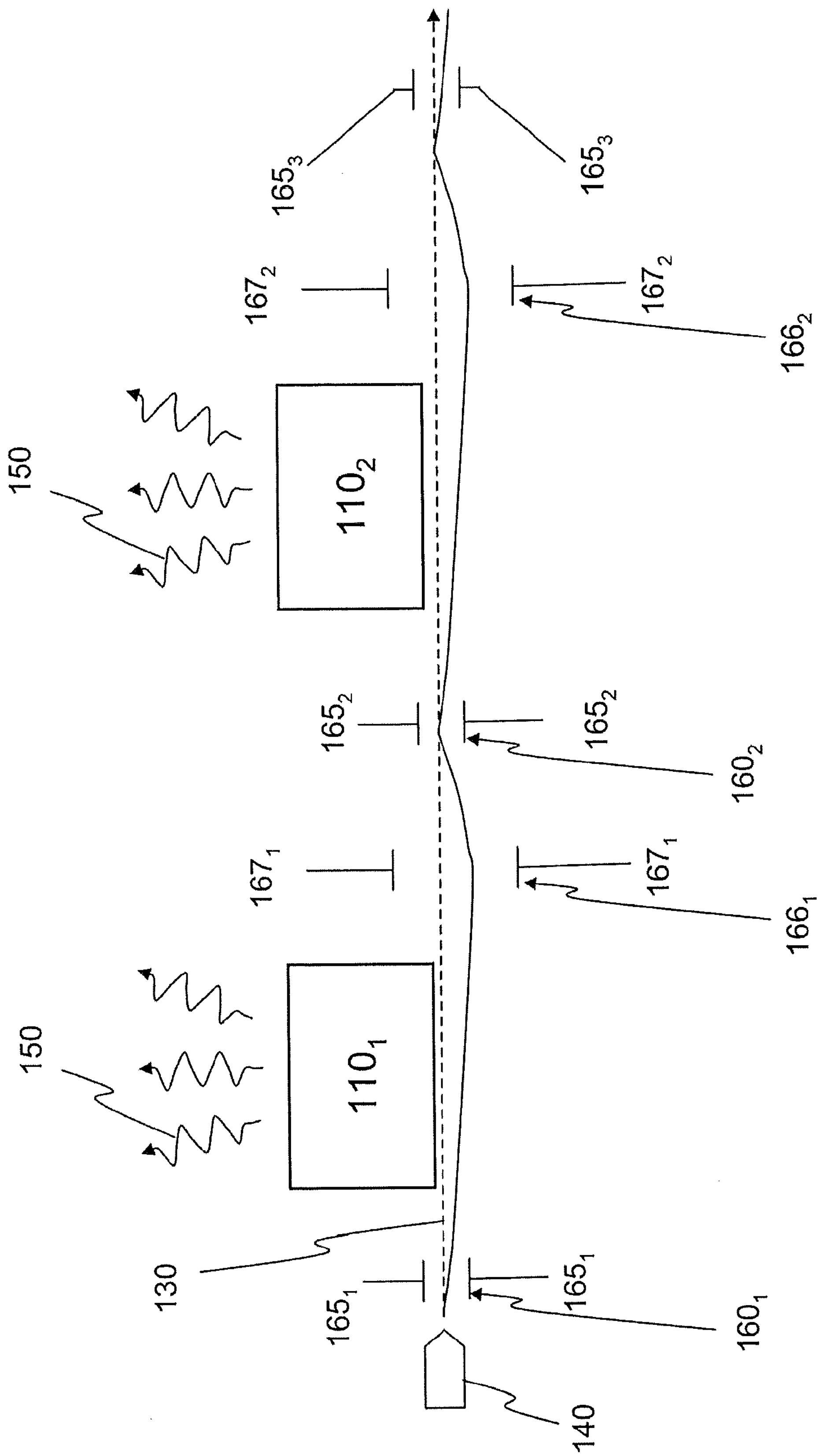

165_3
165_3
167_2
167_2
166_2
150
110_2
165_2
165_2
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167_1
167_1
166_1
150
110_1
130
165_1
165_1
160_1
140

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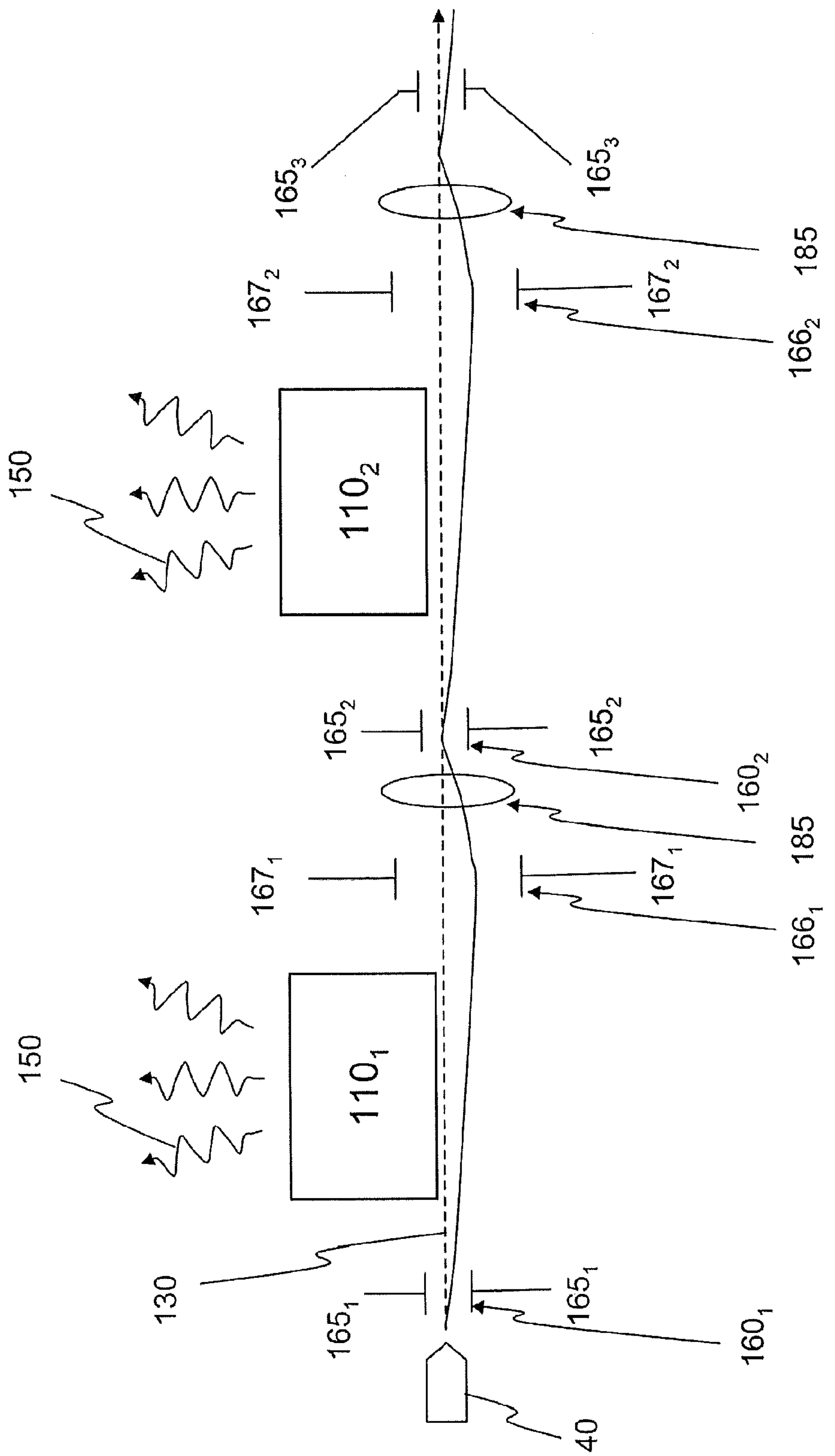

165_3
165_3
185
167_2
167_2
166_2
150
110_2
165_2
165_2
160_2
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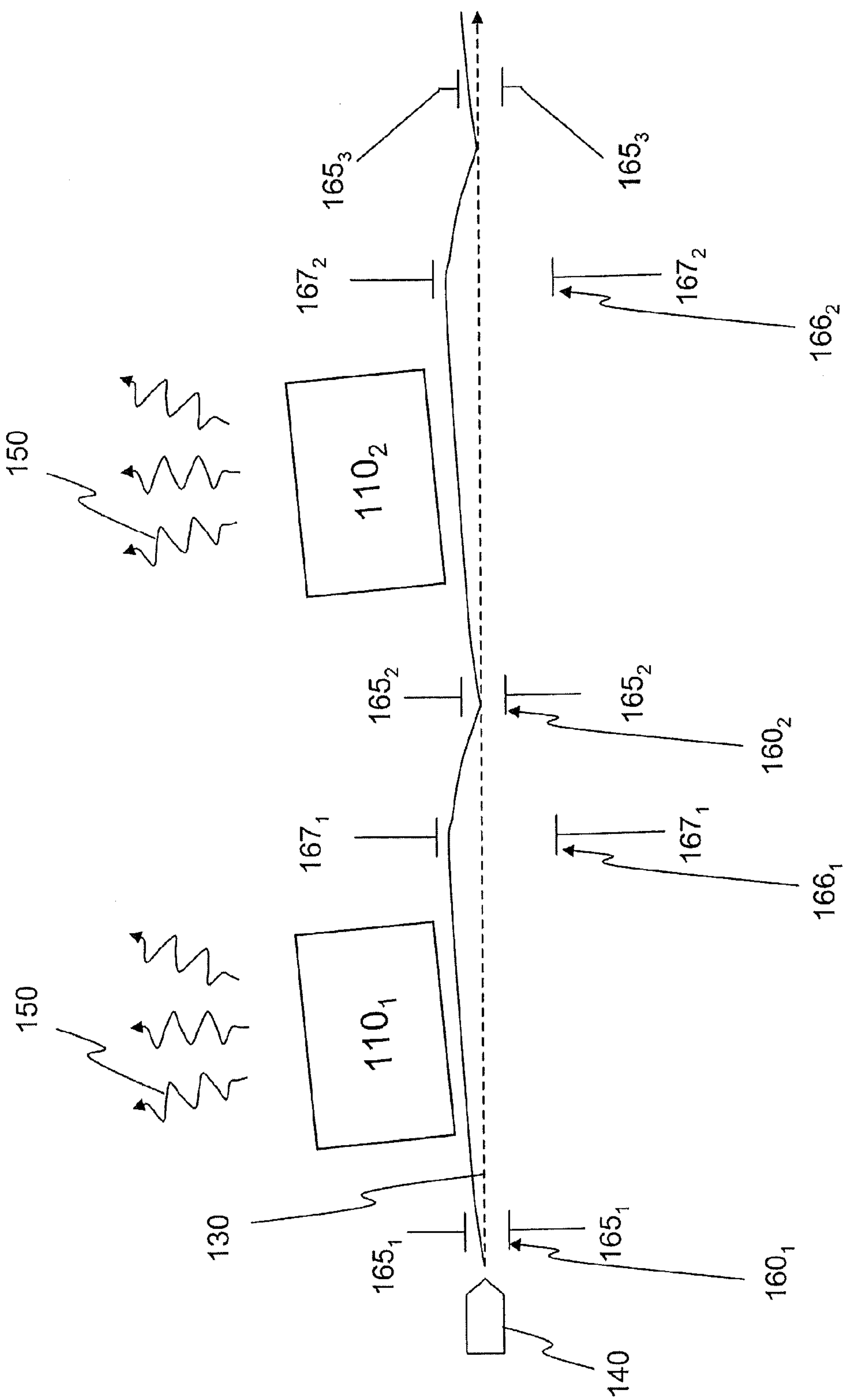
167_1
167_1
166_1
150
110_1
130
165_1
165_1
160_1
140

Figure 21B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150
110_1
110_2
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165_2
165_2
165_3
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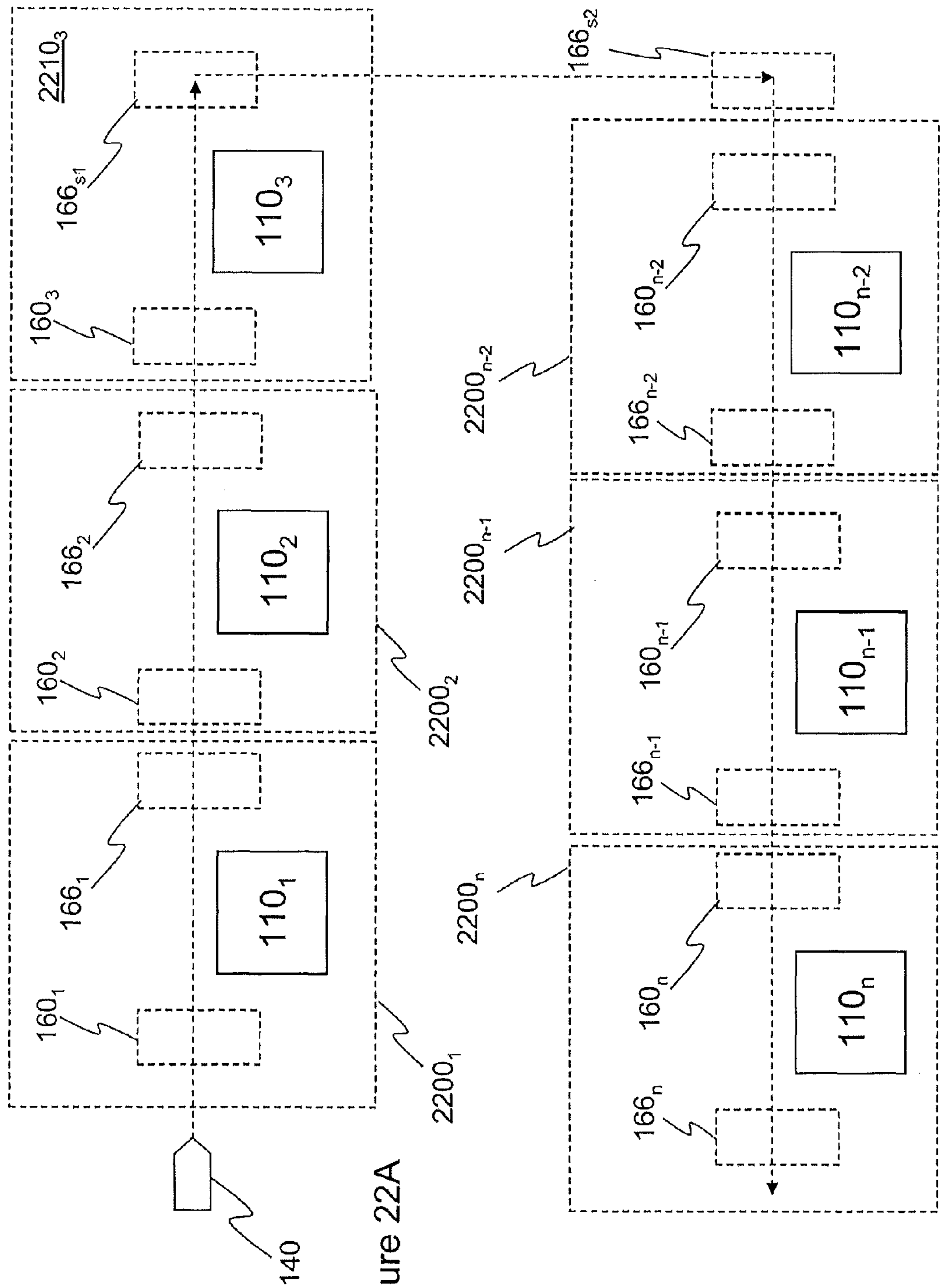
160_1
160_2
130
140

Figure 21C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166_{s2}
110_3
160_3
166_2
110_2
160_2
2200_2
166_1
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2200_1
140
2200_{n-2}
160_{n-2}
110_{n-2}
166_{n-2}
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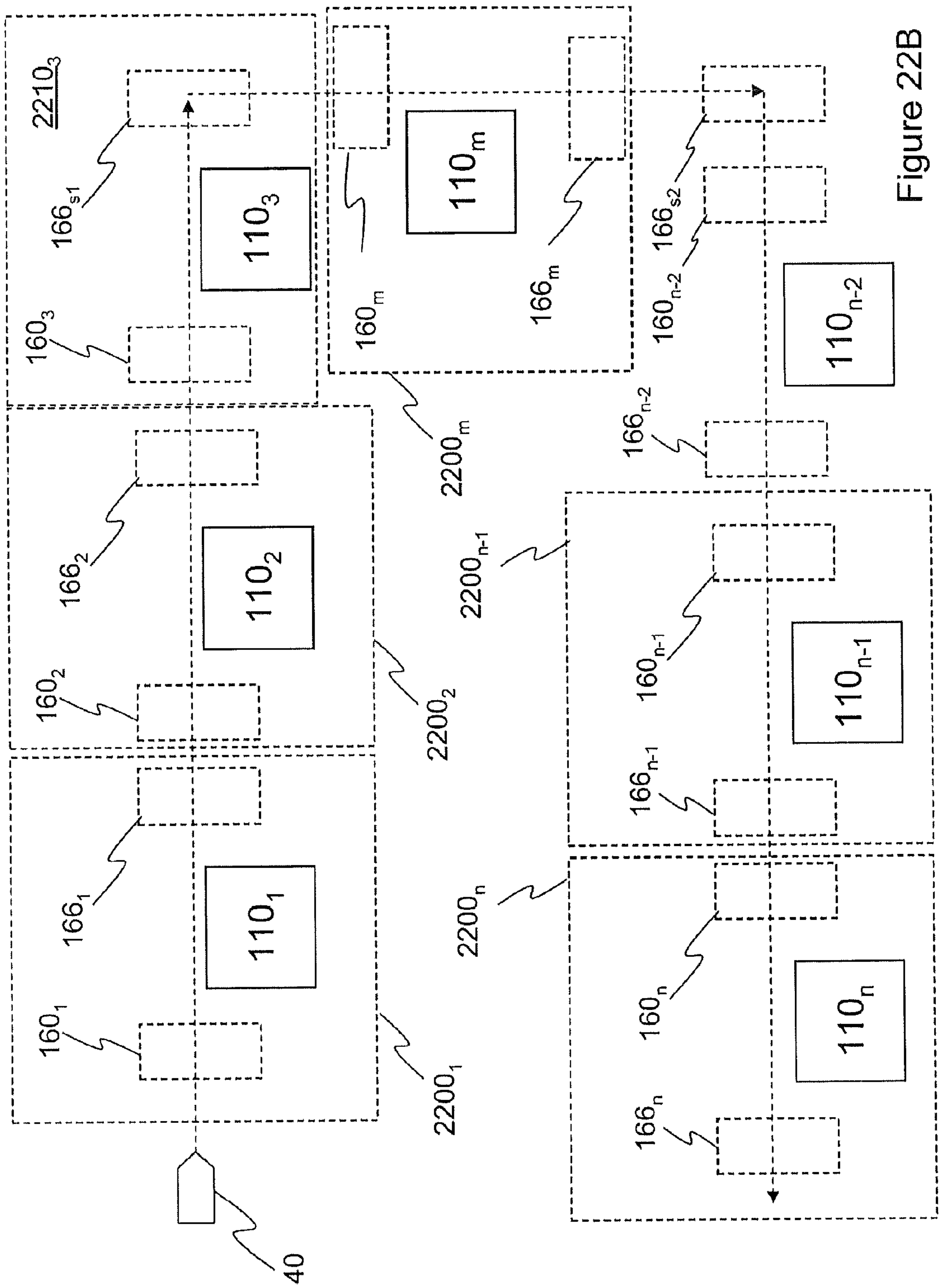
2200_n
160_n
110_n
166_n

Figure 22A



$\underline{2210_3}$
166_{s1}
110_3
160_3
160_m
110_m
166_m
2200_m
166_{s2}
160_{n-2}
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110_{n-1}
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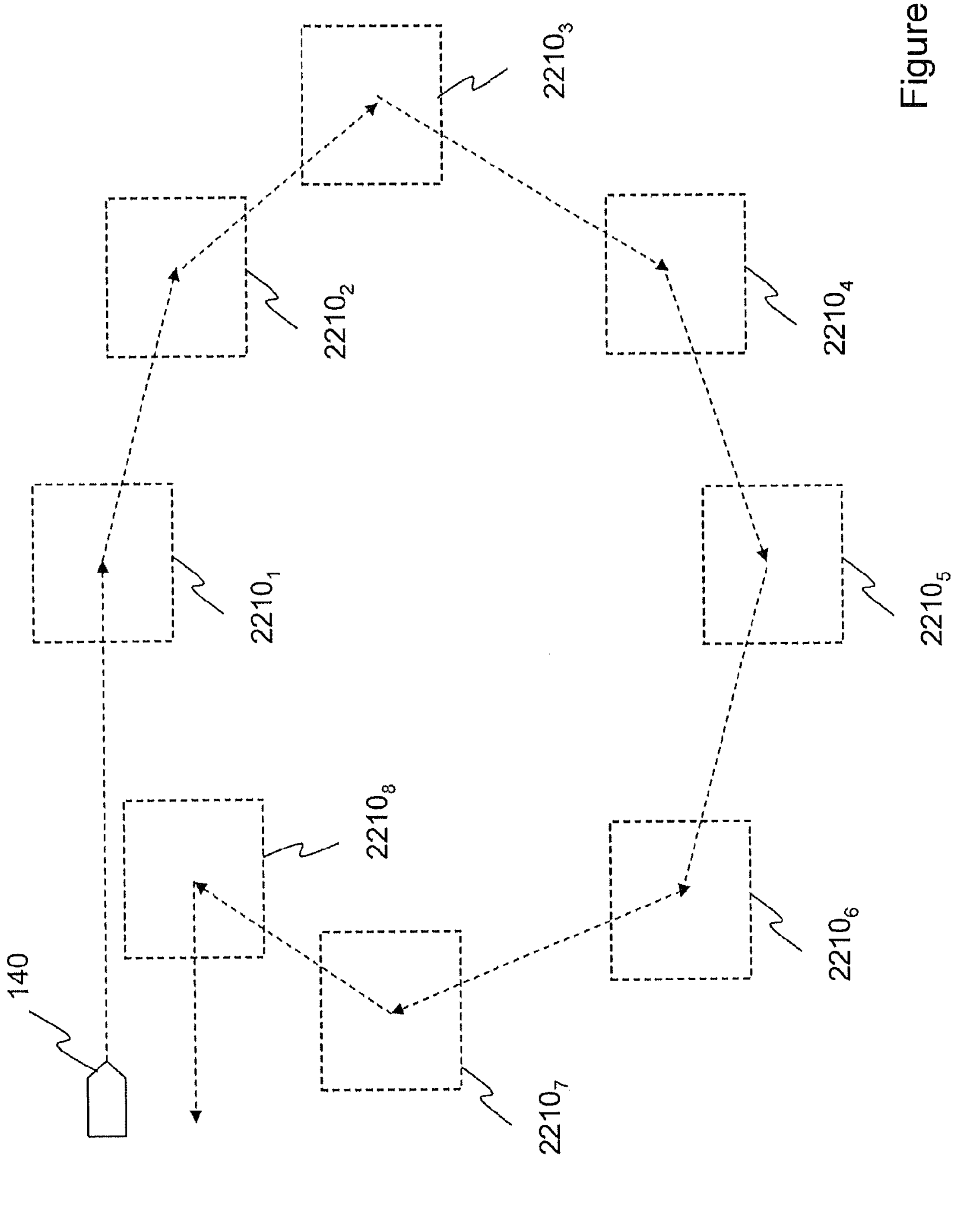
Figure 22B



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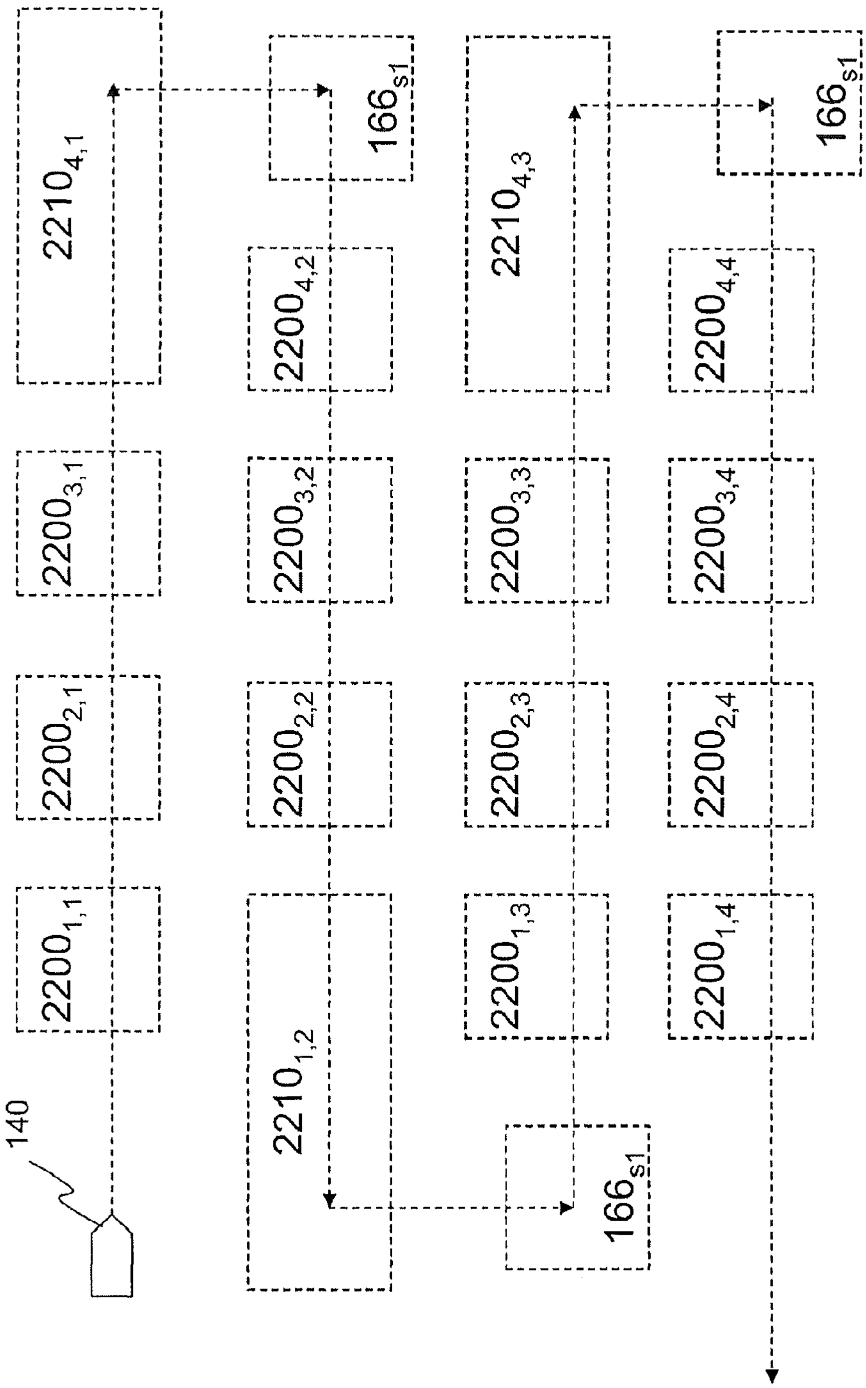
140
2200$_{1,1}$
2200$_{2,1}$
2200$_{3,1}$
2210$_{4,1}$
2210$_{1,2}$
2200$_{2,2}$
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2200$_{4,2}$
166$_{s1}$
166$_{s1}$
2200$_{1,3}$
2200$_{2,3}$
2200$_{3,3}$
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166$_{s1}$

Figure 22D

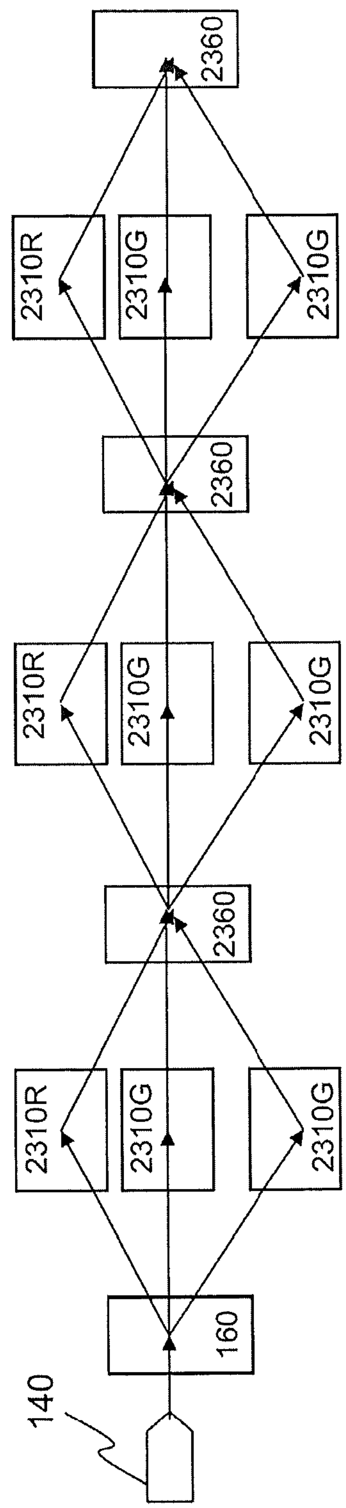
2360
2310R
2310G
2310G
2360
2310R
2310G
2310G
2360
2310R
2310G
2310G
160
140

Figure 23

SWITCHING MICRO-RESONANT STRUCTURES BY MODULATING A BEAM OF CHARGED PARTICLES

CROSS-REFERENCE TO CO-PENDING APPLICATIONS

The present invention is a continuation of U.S. patent application Ser. No. 12/329,866, filed Dec. 8, 2008, now U.S. Pat. No. 8,384,042 entitled "Switching Micro-Resonant Structures By Modulating a Beam of Charged Particles," which is a continuation of U.S. patent application Ser. No. 11/325,534, filed Jan. 5, 2006, now U.S. Pat. No. 7,586,097 entitled "Switching Micro-Resonant Structures Using at Least One Director," and is related to the following U.S. Patent applications: (1) U.S. patent application Ser. No. 11/238,991, filed Sep. 30, 2005, entitled "Ultra-Small Resonating Charged Particle Beam Modulator;" (2) U.S. patent application Ser. No. 10/917,511, filed on Aug. 13, 2004, entitled "Patterning Thin Metal Film by Dry Reactive Ion Etching," (3) U.S. application Ser. No. 11/203,407, filed on Aug. 15, 2005, entitled "Method Of Patterning Ultra-Small Structures," (4) U.S. application Ser. No. 11/243,476, filed on Oct. 5, 2005, entitled "Structures And Methods For Coupling Energy From An Electromagnetic Wave," which is now U.S. Pat. No. 7,253,426, (5) U.S. application Ser. No. 11/243,477, filed on Oct. 5, 2005, entitled "Electron beam induced resonance," (6) U.S. application Ser. No. 11/325,432, entitled "Resonant Structure-Based Display," filed on Jan. 5, 2006; (7) U.S. application Ser. No. 11/325,571, entitled "Switching Micro-Resonant Structures By Modulating A Beam Of Charged Particles," filed on Jan. 5, 2006; and (8) U.S. application Ser. No. 11/325,448, entitled "Selectable Frequency Light Emitter," filed on Jan. 5, 2006, which are all commonly owned with the present application, the entire contents of each of which are incorporated herein by reference.

FIELD OF INVENTION

This relates to the production of electromagnetic radiation (EMR) at selected frequencies and to the coupling of high frequency electromagnetic radiation to elements on a chip or a circuit board.

INTRODUCTION

In the above-identified patent applications, the design and construction methods for ultra-small structures for producing electromagnetic radiation are disclosed. When using micro-resonant structures, it is possible to use the same source of charged particles to cause multiple resonant structures to emit electromagnetic radiation. This reduces the number of sources that are required for multi-element configurations, such as displays with plural rows (or columns) of pixels.

In one such embodiment, at least one deflector is placed in between first and second resonant structures. After the beam passes by the first resonant structure, it is directed to a center path corresponding to the second resonant structure. The amount of deflection needed to direct the beam to the center path is based on the amount of deflection, if any, that the beam underwent as it passed by the first resonant structure. This process can be repeated in series as necessary to produce a set of resonant structures in series.

BRIEF DESCRIPTION OF THE DRAWINGS

The following description, given with respect to the attached drawings, may be better understood with reference to the non-limiting examples of the drawings, wherein:

FIG. **1** is a generalized block diagram of a generalized resonant structure and its charged particle source;

FIG. **2**A is a top view of a non-limiting exemplary resonant structure for use with the present invention;

FIG. **2**B is a top view of the exemplary resonant structure of FIG. **2**A with the addition of a backbone;

FIGS. **2**C-**2**H are top views of other exemplary resonant structures for use with the present invention;

FIG. **3** is a top view of a single color element having a first period and a first "finger" length according to one embodiment of the present invention;

FIG. **4** is a top view of a single color element having a second period and a second "finger" length according to one embodiment of the present invention;

FIG. **5** is a top view of a single color element having a third period and a third "finger" length according to one embodiment of the present invention;

FIG. **6**A is a top view of a multi-color element utilizing two deflectors according to one embodiment of the present invention;

FIG. **6**B is a top view of a multi-color element utilizing a single, integrated deflector according to one embodiment of the present invention;

FIG. **6**C is a top view of a multi-color element utilizing a single, integrated deflector and focusing optics according to one embodiment of the present invention;

FIG. **6**D is a top view of a multi-color element utilizing plural deflectors along various points in the path of the beam according to one embodiment of the present invention;

FIG. **7** is a top view of a multi-color element utilizing two serial deflectors according to one embodiment of the present invention;

FIG. **8** is a perspective view of a single wavelength element having a first period and a first resonant frequency or "finger" length according to one embodiment of the present invention;

FIG. **9** is a perspective view of a single wavelength element having a second period and a second "finger" length according to one embodiment of the present invention;

FIG. **10** is a perspective view of a single wavelength element having a third period and a third "finger" length according to one embodiment of the present invention;

FIG. **11** is a perspective view of a portion of a multi-wavelength element having wavelength elements with different periods and "finger" lengths;

FIG. **12** is a top view of a multi-wavelength element according to one embodiment of the present invention;

FIG. **13** is a top view of a multi-wavelength element according to another embodiment of the present invention;

FIG. **14** is a top view of a multi-wavelength element utilizing two deflectors with variable amounts of deflection according to one embodiment of the present invention;

FIG. **15** is a top view of a multi-wavelength element utilizing two deflectors according to another embodiment of the present invention;

FIG. **16** is a top view of a multi-intensity element utilizing two deflectors according to another embodiment of the present invention;

FIG. **17**A is a top view of a multi-intensity element using plural inline deflectors;

FIG. **17**B is a top view of a multi-intensity element using plural attractive deflectors above the path of the beam;

FIG. **17**C is a view of a first deflectable beam for turning the resonant structures on and off without needing a separate data input on the source of charged particles and without having to turn off the source of charged particles;

FIG. **17**D is a view of a second deflectable beam for turning the resonant structures on and off without needing a separate data input on the source of charged particles and without having to turn off the source of charged particles;

FIG. **18**A is a top view of a multi-intensity element using finger of varying heights;

FIG. **18**B is a top view of a multi-intensity element using finger of varying heights;

FIG. **19**A is a top view of a fan-shaped resonant element that enables varying intensity based on the amount of deflection of the beam;

FIG. **19**B is a top view of another fan-shaped resonant element that enables varying intensity based on the amount of deflection of the beam; and

FIG. **20** is a microscopic photograph of a series of resonant segments;

FIG. **21**A is a high-level block diagram of a set of "normally on" resonant structures in series which are all excited by the same source of charged particles;

FIG. **21**B is a high-level block diagram of a set of "normally on" resonant structures in series which are all excited by the same source of charged particles after undergoing refocusing by at least one focusing element between resonant structures;

FIG. **21**C is a high-level block diagram of a set of "normally off" resonant structures in series which are all excited by the same source of charged particles;

FIG. **22**A is a high-level block diagram of a series of resonant structures laid out in rows in which the direction of the beam is reversed;

FIG. **22**B is a high-level block diagram of a series of resonant structures laid out in a U-shaped pattern in which the direction of the beam is changed at least twice;

FIGS. **22**C-**22**D are high-level diagrams of additional shapes of paths that a beam can take when exciting plural resonant structures; and

FIG. **23** is a high-level diagram of a series of multi-color resonant structures which are driven by the same source.

DISCUSSION OF THE PREFERRED EMBODIMENTS

Turning to FIG. **1**, according to the present invention, a wavelength element **100** on a substrate **105** (such as a semiconductor substrate or a circuit board) can be produced from at least one resonant structure **110** that emits light (such as infrared light, visible light or ultraviolet light or any other electromagnetic radiation (EMR) **150** at a wide range of frequencies, and often at a frequency higher than that of microwave). The EMR **150** is emitted when the resonant structure **110** is exposed to a beam **130** of charged particles ejected from or emitted by a source of charged particles **140**. The source **140** is controlled by applying a signal on data input **145**. The source **140** can be any desired source of charged particles such as an electron gun, a cathode, an ion source, an electron source from a scanning electron microscope, etc.

Exemplary resonant structures are illustrated in FIGS. **2**A-**2**H. As shown in FIG. **2**A, a resonant structure **110** may comprise a series of fingers **115** which are separated by a spacing **120** measured as the beginning of one finger **115** to the beginning of an adjacent finger **115**. The finger **115** has a thickness that takes up a portion of the spacing between fingers **115**. The fingers also have a length **125** and a height (not shown). As illustrated, the fingers of FIG. **2**A are perpendicular to the beam **130**.

Resonant structures **110** are fabricated from resonating material (e.g., from a conductor such as metal (e.g., silver, gold, aluminum and platinum or from an alloy) or from any other material that resonates in the presence of a charged particle beam). Other exemplary resonating materials include carbon nanotubes and high temperature superconductors.

When creating any of the elements **100** according to the present invention, the various resonant structures can be constructed in multiple layers of resonating materials but are preferably constructed in a single layer of resonating material (as described above).

In one single layer embodiment, all the resonant structures **110** of a resonant element **100** are etched or otherwise shaped in the same processing step. In one multi-layer embodiment, the resonant structures **110** of each resonant frequency are etched or otherwise shaped in the same processing step. In yet another multi-layer embodiment, all resonant structures having segments of the same height are etched or otherwise shaped in the same processing step. In yet another embodiment, all of the resonant elements **100** on a substrate **105** are etched or otherwise shaped in the same processing step.

The material need not even be a contiguous layer, but can be a series of resonant elements individually present on a substrate. The materials making up the resonant elements can be produced by a variety of methods, such as by pulsed-plating, depositing, sputtering or etching. Preferred methods for doing so are described in co-pending U.S. application Ser. No. 10/917,571, filed on Aug. 13, 2004, entitled "Patterning Thin Metal Film by Dry Reactive Ion Etching," and in U.S. application Ser. No. 11/203,407, filed on Aug. 15, 2005, entitled "Method Of Patterning Ultra-Small Structures," both of which are commonly owned at the time of filing, and the entire contents of each of which are incorporated herein by reference.

At least in the case of silver, etching does not need to remove the material between segments or posts all the way down to the substrate level, nor does the plating have to place the posts directly on the substrate. Silver posts can be on a silver layer on top of the substrate. In fact, we discovered that, due to various coupling effects, better results are obtained when the silver posts are set on a silver layer, which itself is on the substrate.

As shown in FIG. **2**B, the fingers of the resonant structure **110** can be supplemented with a backbone. The backbone **112** connects the various fingers **115** of the resonant structure **110** forming a comb-like shape on its side. Typically, the backbone **112** would be made of the same material as the rest of the resonant structure **110**, but alternate materials may be used. In addition, the backbone **112** may be formed in the same layer or a different layer than the fingers **110**. The backbone **112** may also be formed in the same processing step or in a different processing step than the fingers **110**. While the remaining figures do not show the use of a backbone **112**, it should be appreciated that all other resonant structures described herein can be fabricated with a backbone also.

The shape of the fingers **115**R (or posts) may also be shapes other than rectangles, such as simple shapes (e.g., circles, ovals, arcs and squares), complex shapes (e.g., such as semi-circles, angled fingers, serpentine structures and embedded structures (i.e., structures with a smaller geometry within a larger geometry, thereby creating more complex resonances)) and those including waveguides or complex cavities. The finger structures of all the various shapes will be collectively referred to herein as "segments." Other exemplary shapes are shown in FIGS. **2**C-**2**H, again with respect to a path of a beam **130**. As can be seen at least from FIG. **2**C, the axis of symmetry of the segments need not be perpendicular to the path of the beam **130**.

Turning now to specific exemplary resonant elements, in FIG. **3**, a wavelength element **100**R for producing electromagnetic radiation with a first frequency is shown as having been constructed on a substrate **105**. (The illustrated embodiments of FIGS. **3**, **4** and **5** are described as producing red, green and blue light in the visible spectrum, respectively. However, the spacings and lengths of the fingers **115**R, **115**G and **115**B of the resonant structures **110**R, **110**G and **110**B, respectively, are for illustrative purposes only and not intended to represent any actual relationship between the period **120** of the fingers, the lengths of the fingers **115** and the frequency of the emitted electromagnetic radiation.) However, the dimensions of exemplary resonant structures are provided in the table below.

Wavelength	Period 120	Segment thickness	Height 155	Length 125	# of fingers in a row
Red	220 nm	110 nm	250-400 nm	100-140 nm	200-300
Green	171 nm	85 nm	250-400 nm	180 nm	200-300
Blue	158 nm	78 nm	250-400 nm	60-120 nm	200-300

As dimensions (e.g., height and/or length) change the intensity of the radiation may change as well. Moreover, depending on the dimensions, harmonics (e.g., second and third harmonics) may occur. For post height, length, and width, intensity appears oscillatory in that finding the optimal peak of each mode created the highest output. When operating in the velocity dependent mode (where the finger period depicts the dominant output radiation) the alignment of the geometric modes of the fingers are used to increase the output intensity. However it is seen that there are also radiation components due to geometric mode excitation during this time, but they do not appear to dominate the output. Optimal overall output comes when there is constructive modal alignment in as many axes as possible.

Other dimensions of the posts and cavities can also be swept to improve the intensity. A sweep of the duty cycle of the cavity space width and the post thickness indicates that the cavity space width and period (i.e., the sum of the width of one cavity space width and one post) have relevance to the center frequency of the resultant radiation. That is, the center frequency of resonance is generally determined by the post/space period. By sweeping the geometries, at given electron velocity v and current density, while evaluating the characteristic harmonics during each sweep, one can ascertain a predictable design model and equation set for a particular metal layer type and construction. Each of the dimensions mentioned about can be any value in the nanostructure range, i.e., 1 nm to 1 μm. Within such parameters, a series of posts can be constructed that output substantial EMR in the infrared, visible and ultraviolet portions of the spectrum and which can be optimized based on alterations of the geometry, electron velocity and density, and metal/layer type. It should also be possible to generate EMR of longer wavelengths as well. Unlike a Smith-Purcell device, the resultant radiation from such a structure is intense enough to be visible to the human eye with only 30 nanoamperes of current.

Using the above-described sweeps, one can also find the point of maximum intensity for given posts. Additional options also exist to widen the bandwidth or even have multiple frequency points on a single device. Such options include irregularly shaped posts and spacing, series arrays of non-uniform periods, asymmetrical post orientation, multiple beam configurations, etc.

As shown in FIG. **3**, a beam **130** of charged particles (e.g., electrons, or positively or negatively charged ions) is emitted from a source **140** of charged particles under the control of a data input **145**. The beam **130** passes close enough to the resonant structure **110**R to excite a response from the fingers and their associated cavities (or spaces). The source **140** is turned on when an input signal is received that indicates that the resonant structure **110**R is to be excited. When the input signal indicates that the resonant structure **110**R is not to be excited, the source **140** is turned off.

The illustrated EMR **150** is intended to denote that, in response to the data input **145** turning on the source **140**, a red wavelength is emitted from the resonant structure **110**R. In the illustrated embodiment, the beam **130** passes next to the resonant structure **110**R which is shaped like a series of rectangular fingers **115**R or posts.

The resonant structure **110**R is fabricated utilizing any one of a variety of techniques (e.g., semiconductor processing-style techniques such as reactive ion etching, wet etching and pulsed plating) that produce small shaped features.

In response to the beam **130**, electromagnetic radiation **150** is emitted there from which can be directed to an exterior of the element **110**.

As shown in FIG. **4**, a green element **100**G includes a second source **140** providing a second beam **130** in close proximity to a resonant structure **110**G having a set of fingers **115**G with a spacing **120**G, a finger length **125**G and a finger height **155**G (see FIG. **9**) which may be different than the spacing **120**R, finger length **125**G and finger height **155**R of the resonant structure **110**R. The finger length **125**, finger spacing **120** and finger height **155** may be varied during design time to determine optimal finger lengths **125**, finger spacings **120** and finger heights **155** to be used in the desired application.

As shown in FIG. **5**, a blue element **100**B includes a third source **140** providing a third beam **130** in close proximity to a resonant structure **110**B having a set of fingers **115**B having a spacing **120**B, a finger length **125**B and a finger height **155**B (see FIG. **10**) which may be different than the spacing **120**R, length **125**R and height **155**R of the resonant structure **110**R and which may be different than the spacing **120**G, length **125**G and height **155**G of the resonant structure **110**G.

The cathode sources of electron beams, as one example of the charged particle beam, are usually best constructed off of the chip or board onto which the conducting structures are constructed. In such a case, we incorporate an off-site cathode with a deflector, diffractor, or switch to direct one or more electron beams to one or more selected rows of the resonant structures. The result is that the same conductive layer can produce multiple light (or other EMR) frequencies by selectively inducing resonance in one of plural resonant structures that exist on the same substrate **105**.

In an embodiment shown in FIG. **6**A, an element is produced such that plural wavelengths can be produced from a single beam **130**. In the embodiment of FIG. **6**A, two deflectors **160** are provided which can direct the beam towards a desired resonant structure **110**G, **110**B or **110**R by providing a deflection control voltage on a deflection control terminal **165**. One of the two deflectors **160** is charged to make the beam bend in a first direction toward a first resonant structure, and the other of the two deflectors can be charged to make the beam bend in a second direction towards a second resonant structure. Energizing neither of the two deflectors **160** allows the beam **130** to be directed to yet a third of the resonant structures. Deflector plates are known in the art and include, but are not limited to, charged plates to which a voltage differential can be applied and deflectors as are used in cathode-ray tube (CRT) displays.

While FIG. **6**A illustrates a single beam **130** interacting with three resonant structures, in alternate embodiments a larger or smaller number of resonant structures can be utilized in the multi-wavelength element **100**M. For example, utilizing only two resonant structures **110**G and **110**B ensures that the beam does not pass over or through a resonant structure as it would when bending toward **110**R if the beam **130** were left on. However, in one embodiment, the beam **130** is turned off while the deflector(s) is/are charged to provide the desired deflection and then the beam **130** is turned back on again.

In yet another embodiment illustrated in FIG. **6**B, the multi-wavelength structure **100**M of FIG. **6**A is modified to utilize a single deflector **160** with sides that can be individually energized such that the beam **130** can be deflected toward the appropriate resonant structure. The multi-wavelength element **100**M of FIG. **6**C also includes (as can any embodiment described herein) a series of focusing charged particle optical elements **600** in front of the resonant structures **110**R, **110**G and **110**B.

In yet another embodiment illustrated in FIG. **6**D, the multi-wavelength structure **100**M of FIG. **6**A is modified to utilize additional deflectors **160** at various points along the path of the beam **130**. Additionally, the structure of FIG. **6**D has been altered to utilize a beam that passes over, rather than next to, the resonant structures **110**R, **110**G and **110**B.

Alternatively, as shown in FIG. **7**, rather than utilize parallel deflectors (e.g., as in FIG. **6**A), a set of at least two deflectors **160***a,b* may be utilized in series. Each of the deflectors includes a deflection control terminal **165** for controlling whether it should aid in the deflection of the beam **130**. For example, with neither of deflectors **160***a,b* energized, the beam **130** is not deflected, and the resonant structure **110**B is excited. When one of the deflectors **160***a,b* is energized but not the other, then the beam **130** is deflected towards and excites resonant structure **110**G. When both of the deflectors **160***a,b* are energized, then the beam **130** is deflected towards and excites resonant structure **110**R. The number of resonant structures could be increased by providing greater amounts of beam deflection, either by adding additional deflectors **160** or by providing variable amounts of deflection under the control of the deflection control terminal **165**.

Alternatively, “directors” other than the deflectors **160** can be used to direct/deflect the electron beam **130** emitted from the source **140** toward any one of the resonant structures **110** discussed herein. Directors **160** can include any one or a combination of a deflector **160**, a diffractor, and an optical structure (e.g., switch) that generates the necessary fields.

While many of the above embodiments have been discussed with respect to resonant structures having beams **130** passing next to them, such a configuration is not required. Instead, the beam **130** from the source **140** may be passed over top of the resonant structures. FIGS. **8**, **9** and **10** illustrate a variety of finger lengths, spacings and heights to illustrate that a variety of EMR **150** frequencies can be selectively produced according to this embodiment as well.

Furthermore, as shown in FIG. **11**, the resonant structures of FIGS. **8**-**10** can be modified to utilize a single source **190** which includes a deflector therein. However, as with the embodiments of FIGS. **6**A-**7**, the deflectors **160** can be separate from the charged particle source **140** as well without departing from the present invention. As shown in FIG. **11**, fingers of different spacings and potentially different lengths and heights are provided in close proximity to each other. To activate the resonant structure **110**R, the beam **130** is allowed to pass out of the source **190** undeflected. To activate the resonant structure **110**B, the beam **130** is deflected after being generated in the source **190**. (The third resonant structure for the third wavelength element has been omitted for clarity.)

While the above elements have been described with reference to resonant structures **110** that have a single resonant structure along any beam trajectory, as shown in FIG. **12**, it is possible to utilize wavelength elements **200**RG that include plural resonant structures in series (e.g., with multiple finger spacings and one or more finger lengths and finger heights per element). In such a configuration, one may obtain a mix of wavelengths if this is desired. At least two resonant structures in series can either be the same type of resonant structure (e.g., all of the type shown in FIG. **2**A) or may be of different types (e.g., in an exemplary embodiment with three resonant structures, at least one of FIG. **2**A, at least one of FIG. **2**C, at least one of FIG. **2**H, but none of the others).

Alternatively, as shown in FIG. **13**, a single charged particle beam **130** (e.g., electron beam) may excite two resonant structures **110**R and **110**G in parallel. As would be appreciated by one of ordinary skill from this disclosure, the wavelengths need not correspond to red and green but may instead be any wavelength pairing utilizing the structure of FIG. **13**.

It is possible to alter the intensity of emissions from resonant structures using a variety of techniques. For example, the charged particle density making up the beam **130** can be varied to increase or decrease intensity, as needed. Moreover, the speed that the charged particles pass next to or over the resonant structures can be varied to alter intensity as well.

Alternatively, by decreasing the distance between the beam **130** and a resonant structure (without hitting the resonant structure), the intensity of the emission from the resonant structure is increased. In the embodiments of FIGS. **3**-**7**, this would be achieved by bringing the beam **130** closer to the side of the resonant structure. For FIGS. **8**-**10**, this would be achieved by lowering the beam **130**. Conversely, by increasing the distance between the beam **130** and a resonant structure, the intensity of the emission from the resonant structure is decreased.

Turning to the structure of FIG. **14**, it is possible to utilize at least one deflector **160** to vary the amount of coupling between the beam **130** and the resonant structures **110**. As illustrated, the beam **130** can be positioned at three different distances away from the resonant structures **110**. Thus, as illustrated at least three different intensities are possible for the green resonant structure, and similar intensities would be available for the red and green resonant structures. However, in practice a much larger number of positions (and corresponding intensities) would be used. For example, by specifying an 8-bit color component, one of 256 different positions would be selected for the position of the beam **130** when in proximity to the resonant structure of that color. Since the resonant structures for different may have different responses to the proximity of the beam, the deflectors are preferably controlled by a translation table or circuit that converts the desired intensity to a deflection voltage (either linearly or non-linearly).

Moreover, as shown in FIG. **15**, the structure of FIG. **13** may be supplemented with at least one deflector **160** which temporarily positions the beam **130** closer to one of the two structures **110**R and **110**G as desired. By modifying the path of the beam **130** to become closer to the resonant structures **110**R and farther away from the resonant structure **110**G, the intensity of the emitted electromagnetic radiation from resonant structure **110**R is increased and the intensity of the emitted electromagnetic radiation from resonant structure **110**G is decreased. Likewise, the intensity of the emitted electromagnetic radiation from resonant structure **110**R can be decreased and the intensity of the emitted electromagnetic radiation from resonant structure **110**G can be increased by modifying the path of the beam **130** to become closer to the resonant structures **110**G and farther away from the resonant structure **110**R. In this way, a multi-resonant structure utilizing beam deflection can act as a color channel mixer.

As shown in FIG. **16**, a multi-intensity pixel can be produced by providing plural resonant structures, each emitting the same dominant frequency, but with different intensities (e.g., based on different numbers of fingers per structure). As illustrated, the color component is capable of providing five different intensities {off, 25%, 50%, 75% and 100%). Such a structure could be incorporated into a device having multiple multi-intensity elements **100** per color or wavelength.

The illustrated order of the resonant structures is not required and may be altered. For example, the most frequently used intensities may be placed such that they require lower amounts of deflection, thereby enabling the system to utilize, on average, less power for the deflection.

As shown in FIG. **17**A, the intensity can also be controlled using deflectors **160** that are inline with the fingers **115** and which repel the beam **130**. By turning on the deflectors at the various locations, the beam **130** will reduce its interactions with later fingers **115** (i.e., fingers to the right in the figure). Thus, as illustrated, the beam can produce six different intensities {off, 20%, 40%, 60%, 80% and 100%} by turning the beam on and off and only using four deflectors, but in practice the number of deflectors can be significantly higher.

Alternatively, as shown in FIG. **17**B, a number of deflectors **160** can be used to attract the beam away from its undeflected path in order to change intensity as well.

In addition to the repulsive and attractive deflectors **160** of FIGS. **17**A and **17**B which are used to control intensity of multi-intensity resonators, at least one additional repulsive deflector **160***r* or at least one additional attractive deflector **160***a*, can be used to direct the beam **130** away from a resonant structure **110**, as shown in FIGS. **17**C and **17**D, respectively. By directing the beam **130** before the resonant structure **110** is excited at all, the resonant structure **110** can be turned on and off, not just controlled in intensity, without having to turn off the source **140**. Using this technique, the source **140** need not include a separate data input **145**. Instead, the data input is simply integrated into the deflection control terminal **165** which controls the amount of deflection that the beam is to undergo, and the beam **130** is left on.

Furthermore, while FIGS. **17**C and **17**D illustrate that the beam **130** can be deflected by one deflector **160***a,r* before reaching the resonant structure **110**, it should be understood that multiple deflectors may be used, either serially or in parallel. For example, deflector plates may be provided on both sides of the path of the charged particle beam **130** such that the beam **130** is cooperatively repelled and attracted simultaneously to turn off the resonant structure **110**, or the deflector plates are turned off so that the beam **130** can, at least initially, be directed undeflected toward the resonant structure **110**.

The configuration of FIGS. **17**A-D is also intended to be general enough that the resonant structure **110** can be either a vertical structure such that the beam **130** passes over the resonant structure **110** or a horizontal structure such that the beam **130** passes next to the resonant structure **110**. In the vertical configuration, the “off” state can be achieved by deflecting the beam **130** above the resonant structure **110** but at a height higher than can excite the resonant structure. In the horizontal configuration, the “off” state can be achieved by deflecting the beam **130** next to the resonant structure **110** but at a distance greater than can excite the resonant structure.

Alternatively, both the vertical and horizontal resonant structures can be turned “off” by deflecting the beam away from resonant structures in a direction other than the undeflected direction. For example, in the vertical configuration, the resonant structure can be turned off by deflecting the beam left or right so that it no longer passes over top of the resonant structure. Looking at the exemplary structure of FIG. **7**, the off-state may be selected to be any one of: a deflection between **110**B and **110**G, a deflection between **110**B and **110**R, a deflection to the right of **110**B, and a deflection to the left of **110**R. Similarly, a horizontal resonant structure may be turned off by passing the beam next to the structure but higher than the height of the fingers such that the resonant structure is not excited.

In yet another embodiment, the deflectors may utilize a combination of horizontal and vertical deflections such that the intensity is controlled by deflecting the beam in a first direction but the on/off state is controlled by deflecting the beam in a second direction.

FIG. **18**A illustrates yet another possible embodiment of a varying intensity resonant structure. (The change in heights of the fingers have been over exaggerated for illustrative purposes). As shown in FIG. **18**A, a beam **130** is not deflected and interacts with a few fingers to produce a first low intensity output. However, as at least one deflector (not shown) internal to or above the source **190** increases the amount of deflection that the beam undergoes, the beam interacts with an increasing number of fingers and results in a higher intensity output.

Alternatively, as shown in FIG. **18**B, a number of deflectors can be placed along a path of the beam **130** to push the beam down towards as many additional segments as needed for the specified intensity.

While deflectors **160** have been illustrated in FIGS. **17**A-**18**B as being above the resonant structures when the beam **130** passes over the structures, it should be understood that in embodiments where the beam **130** passes next to the structures, the deflectors can instead be next to the resonant structures.

FIG. **19**A illustrates an additional possible embodiment of a varying intensity resonant structure according to the present invention. According to the illustrated embodiment, segments shaped as arcs are provided with varying lengths but with a fixed spacing between arcs such that a desired frequency is emitted. (For illustrative purposes, the number of segments has been greatly reduced. In practice, the number of segments would be significantly greater, e.g., utilizing hundreds of segments.) By varying the lengths, the number of segments that are excited by the deflected beam changes with the angle of deflection. Thus, the intensity changes with the angle of deflection as well. For example, a deflection angle of zero excites 100% of the segments. However, at half the maximum angle 50% of the segments are excited. At the maximum angle, the minimum number of segments are excited. FIG. **19**B provides an alternate structure to the structure of FIG. **19**A but where a deflection angle of zero excites the minimum number of segments and at the maximum angle, the maximum number of segments are excited

While the above has been discussed in terms of elements emitting red, green and blue light, the present invention is not so limited. The resonant structures may be utilized to produce a desired wavelength by selecting the appropriate parameters (e.g., beam velocity, finger length, finger period, finger height, duty cycle of finger period, etc.). Moreover, while the above was discussed with respect to three-wavelengths per element, any number (n) of wavelengths can be utilized per element.

As should be appreciated by those of ordinary skill in the art, the emissions produced by the resonant structures **110** can additionally be directed in a desired direction or otherwise altered using any one or a combination of: mirrors, lenses and filters.

The resonant structures (e.g., **110**R, **110**G and **110**B) are processed onto a substrate **105** (FIG. **3**) (such as a semiconductor substrate or a circuit board) and can provide a large number of rows in a real estate area commensurate in size with an electrical pad (e.g., a copper pad).

The resonant structures discussed above may be used for actual visible light production at variable frequencies. Such applications include any light producing application where incandescent, fluorescent, halogen, semiconductor, or other light-producing device is employed. By putting a number of resonant structures of varying geometries onto the same substrate **105**, light of virtually any frequency can be realized by aiming an electron beam at selected ones of the rows.

FIG. **20** shows a series of resonant posts that have been fabricated to act as segments in a test structure. As can be seen, segments can be fabricated having various dimensions.

The above discussion has been provided assuming an idealized set of conditions—i.e., that each resonant structure emits electromagnetic radiation having a single frequency. However, in practice the resonant structures each emit EMR at a dominant frequency and at least one "noise" or undesired frequency. By selecting dimensions of the segments (e.g., by selecting proper spacing between resonant structures and lengths of the structures) such that the intensities of the noise frequencies are kept sufficiently low, an element **100** can be created that is applicable to the desired application or field of use. However, in some applications, it is also possible to factor in the estimate intensity of the noise from the various resonant structures and correct for it when selecting the number of resonant structures of each color to turn on and at what intensity. For example, if red, green and blue resonant structures **110**R, **110**G and **100**B, respectively, were known to emit (1) 10% green and 10% blue, (2) 10% red and 10% blue and (3) 10% red and 10% green, respectively, then a grey output at a selected level ($level_s$) could be achieved by requesting each resonant structure output $level_s/(1+0.1+0.1)$ or $level_s/1.2$.

As shown in FIGS. **21**A and **21**B, plural resonant structures can be concatenated in series and driven by the same source **140** of charged particles. In FIG. **21**A, the source **140** emits a beam **130** of charged particles. In such a "normally on" configuration, if the resonant structure $\mathbf{110}_1$ is to be excited, then the deflectors $\mathbf{160}_1$ are not energized, and the beam **130** is allowed to pass the resonant structure $\mathbf{110}_1$ undeflected. Since the beam **130** is undeflected, the recentering deflectors $\mathbf{166}_1$ need not be energized either using their control terminals $\mathbf{167}_1$.

In the same "normally on" configuration, if the resonant structure $\mathbf{110}_1$ is not to be excited, then the deflectors $\mathbf{160}_1$ are energized using deflection control terminal $\mathbf{165}_1$, and the beam **130** is deflected away from the resonant structure $\mathbf{110}_1$. Since it is deflected, the beam **130** must be recentered while approaching the resonant structure $\mathbf{110}_2$. The recentering is performed using at least one recentering deflector $\mathbf{166}_1$ which is controlled using its corresponding control terminal $\mathbf{167}_1$.

The process is then repeated for the resonant structure $\mathbf{110}_2$ which is turned on or off by at least one deflector $\mathbf{160}_2$ using its corresponding at least one deflection control terminal $\mathbf{165}_2$. The process is repeated for as many resonant structures **110** as are arranged in series. In this way, the state (i.e., off, partially on, or fully on) of each resonant structure $\mathbf{110}_i$ can be controlled by an amount of deflection produced by its corresponding deflector $\mathbf{160}_i$, allowing the beam **130** to remain on and still selectively excite plural resonant structures using only a single beam **130**.

As shown in FIG. **21**B, between resonant structures **110**, a focusing element **185** can be included such that the beam **130** is focused before passing through or while within the deflection range of the deflector(s) $\mathbf{165}_2$ of the adjacent resonant structure $\mathbf{110}_2$.

As an alternative to the "normally on" configuration of FIGS. **21**A and **21**B, a set of resonant structures in series can be arranged in a "normally off" configuration as well. In such a "normally off" configuration, if the resonant structure $\mathbf{110}_1$ is to be excited, then the at least one deflector $\mathbf{160}_1$ is energized, and the beam **130** is deflected sufficiently to excite at least a portion of the resonant structure $\mathbf{110}_1$, depending on the intensity at which the resonant structure $\mathbf{110}_1$ is to emit. Since the beam **130** is deflected, at least one recentering deflector $\mathbf{166}_1$ must also be energized using its control terminals $\mathbf{167}_1$. In the same "normally off" configuration, if the resonant structure $\mathbf{110}_1$ is not to be excited, then the deflectors $\mathbf{160}_1$ are not energized using deflection control terminal $\mathbf{165}_1$, and the beam **130** is left undeflected and does not excite the resonant structure $\mathbf{110}_1$. Since it is undeflected, the beam **130** need not be recentered using recentering deflector $\mathbf{166}_1$ while approaching the resonant structure $\mathbf{110}_2$. However, in a configuration including a focusing element **185** (as in FIG. **21**B), the beam **130** may pass through the focusing element **185**, whether or not the beam is deflected.

FIG. **22**A shows a high-level image of a series of resonant structures, such as the resonant structures of FIG. **21**A (but with control terminals removed to aid clarity). Each deflector $\mathbf{160}_i$, resonant structure $\mathbf{110}_i$ and recentering deflector $\mathbf{166}_i$ can be thought of as a resonant group $\mathbf{2200}_i$, and FIG. **22**A separately identifies five such resonant groups ($\mathbf{2200}_1$, $\mathbf{2200}_2$, $\mathbf{2200}_{n-2}$, $\mathbf{2200}_{n-1}$ and $\mathbf{2200}_n$). FIG. **22**A also illustrates a special resonant group $\mathbf{2210}_3$ which includes a special recentering deflector $\mathbf{166}_{s1}$ that bends the beam **130** from a first direction to a second direction. The illustrated embodiment also includes a second special recentering deflector $\mathbf{166}_{s2}$ that bends the beam **130** from the second direction to a third direction (illustrated as opposite the first direction). The same beam **130** then passes additional resonant structures (of which only three are illustrated). It is to be understood that "n" resonant structures can be excited from the same beam **130**, where n is greater than or equal to 1.

As would be appreciated by one of ordinary skill in the art, the number of resonant structures **110** or resonant groups **2200** that can be connected in series and the shape of the path of the beam can be varied. FIG. **22**B illustrates that a U-shaped pattern allows at least one additional resonant group $\mathbf{2200}_m$ to be connected in series. That additional resonant group $\mathbf{2200}_m$ includes a resonant structure $\mathbf{110}_m$ that is oriented in a direction different than the directions of FIG. **22**A. As illustrated, the orientation of the resonant structure $\mathbf{110}_m$ could be turned ninety degrees compared to the resonant structures $\mathbf{110}_1$-$\mathbf{110}_3$ and $\mathbf{110}_{n-2}$-$\mathbf{110}_n$ of FIG. **22**A.

As illustrated in FIG. **22**C, the path of the beam can also be made circular or oval by using special resonant groups **2210**.

Alternatively, as shown in FIG. **22**D, a matrix of elements can be created from a single source **140** using a mixture of resonant groups (e.g., $\mathbf{2200}_{1,1}$ and $\mathbf{2200}_{1,2}$) and special resonant groups (e.g., $\mathbf{2210}_{4,1}$). Such a matrix can be used is a display such as a computer monitor or a television screen.

FIG. **23** illustrates that the same technique that has been described above with respect to arranging a set of resonant groups (having a single resonant structure per group) in series is also applicable to multi-color elements with plural frequencies per element. As illustrated in FIG. **23**, a first set of red, green and blue resonant groups (**2310**R, **2310**G, and **2310**B) and their intensities (if any) are selected using a deflector **160**.

(If none of the resonant groups are to be turned on, the beam can be deflected in the direction of any of the resonant structures but a sufficient distance away such that none of the resonant structures are actually excited.) The resonant groups further include a recentering deflector (not shown) which directs the beam back towards a special deflector **2360** which can compensate for the amount of deflection that the beam underwent before arriving at the deflector **2360**. This enables the beam **130** to be recentered (and optionally refocused) before or while being passed on to an adjacent set of resonant structures (either single-frequency or multi-frequency).

If a most common series of colors is known in advance, the locations and order of the colors can be laid out such that the most common series of colors requires the least amount of deflection. This reduces the energy consumption required to achieve the most common color arrangement. For example, as shown in FIG. **23**, an all-green series of emitters requires the least amount of deflection and therefore energy.

Additional details about the manufacture and use of such resonant structures are provided in the above-referenced co-pending applications, the contents of which are incorporated herein by reference.

The structures of the present invention may include a multi-pin structure. In one embodiment, two pins are used where the voltage between them is indicative of what frequency band, if any, should be emitted, but at a common intensity. In another embodiment, the frequency is selected on one pair of pins and the intensity is selected on another pair of pins (potentially sharing a common ground pin with the first pair). In a more digital configuration, commands may be sent to the device (1) to turn the transmission of EMR on and off, (2) to set the frequency to be emitted and/or (3) to set the intensity of the EMR to be emitted. A controller (not shown) receives the corresponding voltage(s) or commands on the pins and controls the director to select the appropriate resonant structure and optionally to produce the requested intensity.

While certain configurations of display structures have been illustrated for the purposes of presenting the basic structures of the present invention, one of ordinary skill in the art will appreciate that other variations are possible which would still fall within the scope of the appended claims.

We claim:

1. A modulated electromagnetic radiation emitter, comprising:

at least one resonant structure configured to resonate at at least one resonant frequency higher than a microwave frequency when exposed to a beam of charged particles from a charged particle generator, and

a director for directing the beam of charged particles away from the at least one resonant structure when the resonant structure is not to resonate.

2. The emitter according to claim **1**, wherein the director is one from the group consisting of: a deflector, a diffractor, or an optical structure.

3. The emitter according to claim **1**, wherein the director comprises at least one deflection plate between the charged particle generator and the at least one resonant structure.

4. The emitter according to claim **1**, wherein the beam of charged particles comprises a beam of electrons.

5. The emitter according to claim **1**, wherein the at least one resonant structure comprises at least one silver-based structure.

6. The emitter according to claim **1**, wherein the at least one resonant structure comprises at least one etched-silver-based structure.

7. The emitter according to claim **1**, wherein the beam of charged particles passes next to the at least one resonant structure and the director directs the beam away from a side of the at least one resonant structure a distance sufficient to prevent the at least one resonant structure from resonating.

8. The emitter according to claim **1**, wherein the beam of charged particles passes above the at least one resonant structure and the director directs the beam away from a top of the at least one resonant structure a distance sufficient to prevent the at least one resonant structure from resonating.

9. A method of selectively producing electromagnetic radiation, comprising:

directing a beam of charged particles towards at least one resonant structure, wherein the at least one resonant structure is configured to resonate at a resonant frequency higher than a microwave frequency when exposed to the beam of charged particles, and

directing the beam of charged particles away from the at least one resonant structure prior to exciting the at least one resonant structure when the resonant structure is not to be excited.

10. The method according to claim **9**, wherein directing comprises directing the beam utilizing a director selected from the group consisting of: a deflector, a diffractor, or an optical structure.

11. The method according to claim **9**, wherein the directing comprises directing the beam utilizing at least one deflection plate between a source of the beam and the at least one resonant structure.

12. The method according to claim **9**, wherein the at least one resonant structure comprises at least one silver-based structure.

13. The method according to claim **9**, wherein the at least one resonant structure comprises at least one etched-silver-based structure.

14. The method according to claim **9**, wherein the beam of charged particles passes next to the at least one resonant structure and the directing comprises directing the beam away from a side of the at least one resonant structure a distance sufficient to prevent the at least one resonant structure from resonating.

15. The method according to claim **9**, wherein the beam of charged particles passes above the at least one resonant structure and the directing comprises directing the beam away from a top of the at least one resonant structure a distance sufficient to prevent the at least one resonant structure from resonating.

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